RELIABILITY ANALYSIS OF MULTI-STORIED BUILDING SUBJECTED TO WIND LOAD

A DISSERTATION
SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE
OF

MASTER OF TECHNOLOGY

IN

STRUCTURAL ENGINEERING

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I, Nishant Khajuria, 2K21/STE/22, student of M.Tech Structural Engineering, hereby declare that the project Dissertation titled "RELIABILITY ANALYSIS OF MULTI-STORIED BUILDING SUBJECTED TO WIND LOAD" which is submitted by me to the Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I hereby certify that the Project Dissertation titled "RELIABILITY ANALYSIS OF MULTI-STORIED BUILDING SUBJECTED TO WIND LOAD" which is submitted by Nishant Khajuria, 2K21/STE/22 Department of Civil Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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ACKNOWLEDGEMENT

I would like to extend my deepest gratitude to all those who have played a significant role in the successful completion of this project. While it is not possible to individually acknowledge every person who has assisted me, I would like to express my sincere appreciation to the following individuals for their exceptional support and guidance.

First and foremost, I am immensely thankful to Dr. Pradeep K. Goyal, my project supervisor, for his unwavering support and invaluable guidance throughout the entirety of this project. Their expertise, constructive feedback, and insightful comments have played a pivotal role in shaping the direction and scope of my study. I am truly grateful for their patience, dedication, and mentorship, which have been instrumental in my research journey.

I am deeply grateful to Prof. V.K. Minocha, Head of Department, Department of Civil Engineering, Delhi Technological University for his support and encouragement in carrying out this project.

I would also like to express my heartfelt appreciation to the faculty and staff of the department for providing me with access to necessary resources and facilities. Their support and encouragement have been invaluable in the successful completion of this project.

Additionally, I would like to extend my sincere gratitude to my family, friends, and colleagues for their constant encouragement and unwavering motivation. Their support has been a source of inspiration throughout my academic endeavours.

I am profoundly grateful to everyone who has contributed to the realization of this project. I deeply value their support and guidance, and I will always cherish the experiences gained from this collaboration.

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ABSTRACT

The reliability-based analysis of engineering structures is a crucial aspect of their design, evaluation, and maintenance. Reliability-based analysis focuses on assessing the probability of failure and ensuring the safety and performance of structures under varying operating conditions and uncertainties. It involves accounting for uncertainties related to material properties, loads, environmental factors, and modeling assumptions. The analysis process typically begins by establishing a mathematical model that accurately represents the structural behavior and its response to applied loads and environmental influences. Probabilistic methods like the First Order Reliability Method (FORM) or Monte Carlo simulation are commonly employed to quantify reliability and estimate the probability of failure. Several key factors are considered in reliability-based analysis, including the selection of appropriate probability distributions for input variables, the definition of failure criteria, and the consideration of aging and deterioration effects over the structure's service life. Reliability indices, such as the probability of failure or safety margin, are calculated to assess the level of reliability and evaluate structural performance. The outcomes of reliability-based analysis support decision-making processes by enabling engineers to optimize designs, determine maintenance requirements, and ensure the safety and reliability of engineering structures. This systematic approach offers a framework to account for uncertainties and manage risks associated with structural performance.

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1	R	Resistance
2	S	Load Effect
3	WD	Dead Load
4	WL	Live Load
5	fy	Yield Strength
6	Z	Section Modulus
7	E	Young's Modulus of Elasticity
8	I	Moment of Inertia
9	P_f	Probability of Failure
10	COV	Coefficient of Variation
11	γ	Load Factor
12	β	Reliability Index
13	σ	Standard Deviation
14	μ	Mean Value
15	Ω	Shape Parameter
16	¥	Scale Parameter
17	t_w	Thickness of web
18	D	Depth of Beam

CHAPTER-1

INTRODUCTION

1.1 GENERAL

Reliability in civil engineering refers to a structure, system as well, or component's capacity to carry out its intended function consistently over a predetermined time period and under predetermined circumstances. It is a measurement of the likelihood that an element or structure will achieve its performance goals and keep up its functionality for the duration of its planned service life. An essential component of civil engineering design and evaluation is reliability analysis. It entails assessing the likelihood of breaking down of an element or structure while considering a number of variables, including the material's qualities, the load placed on it, the impacts of the environment, and any associated uncertainties. Making educated judgements concerning the design, upkeep, and security of civil infrastructure is possible with the use of reliability metrics.

Reliability analysis employs statistical techniques to model uncertainties and variations in input parameters affecting the performance of structures or components. These techniques include probabilistic modelling, stochastic analysis, and reliability-based design. By accounting for uncertainties and variability, engineers can determine appropriate safety margins to ensure reliable performance throughout the expected lifespan.

Reliability assessment is particularly important in critical infrastructure projects such as bridges, dams, nuclear power plants, and offshore structures, where failures can have severe consequences in terms of safety, economic losses, and environmental impact. By incorporating reliability analysis into the design process, we can optimize the use of materials, reduce costs, and enhance the overall performance and safety of civil engineering projects.

1.2 PARAMETERS FOR RELIABILITY ANALYSIS

Reliability analysis of buildings involves the consideration of several parameters to assess their performance, safety, and durability. These parameters are utilized to quantify uncertainties related to material properties, loading conditions, and environmental factors. The key parameters commonly employed in reliability analysis for buildings are:

1. Load Parameters:

Dead Load: The permanent weight of the building and its components, such as walls, floors, and roofs.

Live Load: The transient and variable loads imposed on the structure, including occupancy, furniture, equipment, and snow loads.

Wind Load: The forces exerted by wind on the building, including wind pressure distribution and wind speed.

2. Material Properties:

Concrete Strength: The characteristic strength of the concrete material used in structural elements.

Steel Strength: The yield strength or ultimate strength of the steel employed in structural components.

Material Variability: The statistical distribution representing variations and uncertainties in material properties, encompassing strength, stiffness, and other relevant characteristics.

3. Resistance Parameters:

Structural Component Strength: The capacity of individual structural elements, such as columns, beams, and connections, to withstand applied loads.

Connection Strength: The capacity of connections between structural elements to resist forces and moments.

Durability: The ability of building materials to endure degradation over time caused by environmental factors like corrosion or deterioration.

4. Environmental Parameters:

Exposure Conditions: The specific environmental circumstances to which the building is exposed, such as temperature, humidity, aggressive chemicals, or marine environments.

Seismic Parameters: Characteristics of seismic activity in the region, encompassing ground motion, site classification, and seismic design parameters.

Climate Data: Climatic factors such as intensity of rainfall, temperature, wind speed, and duration of exposure to different weather conditions.

5. Uncertainty Parameters:

Probability Distributions: Statistical distributions employed to represent uncertainties in loadings, material properties, and resistance parameters.

Reliability Index: A measure of safety and reliability level, often expressed through indices like probability of failure or safety margin.

6. Service Life Parameters:

Design Life: The intended duration for which the building is designed to fulfill its function without excessive deterioration or performance loss.

Maintenance and Inspection: Frequency and effectiveness of maintenance activities, inspections, and repairs to ensure continued performance and safety of the building.

By considering these parameters, probabilistic analysis such as reliability analysis, can be conducted to evaluate the probability of failure or performance exceeding predetermined thresholds. Utilizing these parameters enables informed decision-making regarding building design, construction, maintenance, and risk management strategies.

1.3 STRUCTURAL RELIABILITY CONSIDERING WIND LOAD

The reliability of a building concerning wind load pertains to its capacity to withstand wind forces without experiencing excessive deflections, deformations, or failures. Wind loads are a critical design consideration, especially in areas prone to high winds, hurricanes, or tornadoes. Evaluating the reliability of a building with respect to wind load involves conducting thorough structural analyses and design checks to ensure that the building can withstand wind loads while maintaining an acceptable level of safety and performance.

Several key factors influencing the reliability of a building in relation to wind load include :

1. Wind load calculations: The initial step in assessing the building's reliability involves determining the magnitude and distribution of wind loads acting on the structure. This entails analyzing the wind climate in the area, estimating wind speeds, and calculating corresponding wind pressures on the building. Precise wind load calculations are essential for ensuring the building's reliability.

2. Structural analysis: Once wind loads are determined, the structural response of the building to these loads needs evaluation. Structural analysis includes creating a model of the building using software and determining the stresses and deformations induced by wind loads. The analysis should consider all relevant loads, such as wind loads, self-weight, and other imposed loads like equipment or snow loads.

3. Design checks: The results of structural analysis are utilized to verify whether the building's components, such as columns, beams, and connections, can withstand the applied wind loads. Design checks involve comparing calculated stresses and strains to allowable values specified in relevant design codes and standards. These checks also ensure that the building meets serviceability requirements, such as deflection limits, vibration criteria, and other functional considerations.

4. Quality control: Ensuring the reliability of a building with respect to wind load also involves implementing quality control measures during the construction process. Quality control measures include testing and verifying the strength and

stiffness of the building's components, such as conducting concrete strength tests and steel tensile tests, to ensure that the actual structure aligns with the design requirements.

1.4 OBJECTIVES AND SCOPE OF STUDY

Following are the objectives of the present study:

- To calculate the Reliability Index of Structural Members under different parameters using different methods of Reliability theory.

- To compare results between the Different types of methods of Reliability Analysis including FORM, SORM, MVFO, Monte Carlo Simulations.

- To calculate Reliability index of Structural components of a Multi storied building based on Indian Standard Codes subjected to different wind load conditions by using Limit state Functions manually and In Software based Reliability Analysis package COMREL.

CHAPTER 2

LITERATURE REVIEW

Structural reliability analysis and design have attracted significant attention and interest from scholars and researchers for an extended period. Over time, numerous scholars have contributed to this field by devising different approaches, methodologies, and design strategies. In the course of this project, guidance was sought from renowned scholars in this area, and their influential papers were reviewed and summarized briefly.

Yi Zhang et al., [2008] the significance of accounting for wind load uncertainties in the reliability analysis of tall buildings is discussed. The authors acknowledge the critical role of wind loads in the design of high-rise structures and the potential impact of uncertainties on structural reliability and safety. These uncertainties stem from factors such as wind speed variations, wind direction changes, turbulence intensity fluctuations, and the dynamic response of the building itself. The authors underscore the necessity of incorporating these uncertainties into the reliability analysis to ensure a more accurate and realistic evaluation of the structure's performance. A method for performing high-rise building reliability analyses while taking wind load uncertainties into account is suggested. To represent the unpredictable nature of wind loads and their effects on structural response, probabilistic approach that uses statistical distributions is presented. They also explore the use of methods like Monte Carlo simulation or response surface methods to measure structural reliability. The paper provides information on the design criteria for the building, the features of wind loads, and the material attributes. The reliability of the structure under several wind load scenarios is then examined using a probabilistic technique. The consequences that ensue are highlighted, highlighting the likelihood of failure and the building's safety buffer.

El Ghoulbzouri Abdelouafi et al.,[2011] The research focuses on the assessment of the reliability of seismic performance for reinforced concrete buildings. The study employed conventional pushover analysis and finite element computations conducted using the ZeusNL software package to examine the seismic behavior of the buildings. The findings suggest that the FORM (First Order Reliability Method) tends to overestimate the probability of failure.

Chen Qingjun et al.,[2014] The research explores the application of the SAP2000 application programming interface (API) and the .NET Framework to conduct reliable assessments of reinforced concrete (RC) structures. The study focuses on utilizing computational methods to evaluate the safety and reliability of RC structures under various loading conditions, including seismic events. The framework used incorporates probabilistic analysis techniques to account for uncertainties associated with material properties, loads, and other relevant factors influencing the structural response.

Chandra S. Putcha.,[1984] The research presents an investigation into the development of an analytical approach for assessing the reliability of beams. The study focuses on utilizing mathematical methods to evaluate the safety and reliability of beams under different load conditions. The author introduces a closed form solution that allows for a more efficient and direct assessment of beam reliability without relying on extensive computational simulations involving the derivation and validation of the proposed closed form solution, considering various parameters such as material properties, loads, and beam geometries that affect the structural behaviour. By employing this closed form solution, the probability of failure and other performance criteria for beams can be evaluated.

Milovan Stanojevn.et.al, [2014] The study investigated the subject of evaluating the dependability of various construction kinds. The main objective of the study is to assess the structural reliability of different engineering structures, including buildings and bridges. To calculate the likelihood of failure or performance limitations being exceeded, the analysis takes uncertainties in variables like material qualities, loads, and conditions in the environment into account. To evaluate structural reliability, the study developed and applied probabilistic techniques and mathematical models. Techniques including reliability-based optimisation, response surface approaches, and Monte Carlo simulation are used. The authors also look at several failure scenarios, including as functional loss, severe deformations, and collapse. A summary of the theoretical underpinnings and methodology used in dependability analysis is provided in this work. It talks on statistical ideas, probability theories, and real-world issues like limit state selection, handling uncertainty, and validating results.

André T. Beck et.al. [2008] The approach to assess the safety of steel columns created to abide by Brazilian building standards NBR8800 and NBR8681 was provided in this study. The process entails a non-linear FE study of column resistance, considering the impacts of residual stresses, initial flaws, and column plastic failure. Additionally, a structural reliability analysis for the columns' reliability index was presented. In ABAQUS, a computer code was created to analyse the columns' reliability. It is considered how residual stresses and geometrical flaws affect column resistance. The reliability assessment takes into account dead and live loads, geometrical flaws, yield stress uncertainty, and elasticity modulus uncertainty. For a number of column layouts, reliability indices are obtained.

CHAPTER-3

PROBABILITY THEORY

3.1 GENERAL

Probability theory and data analysis are essential components in evaluating the reliability of engineering structures. Reliability refers to a structure's ability to perform its intended function without failure for a specified duration. These principles are used to assess the probability of failure, estimate the remaining lifespan of structures, and make informed decisions regarding maintenance and design enhancements. Probability theory provides a mathematical framework for quantifying uncertainty and analyzing the likelihood of different events. By employing probability distributions and statistical techniques, the probability of failure is evaluated to determine appropriate safety margins for the structure.

3.2 DATA ANALYSIS

Data analysis plays a crucial role in reliability assessment for engineering structures. This involves collection of data from diverse sources, including field measurements, laboratory tests, and historical records, to gain insights into structural behavior and performance. Through rigorous data analysis, identification and detection of patterns, anomalies, and meaningful information is extracted.

Data analysis techniques help to estimate statistical properties of relevant parameters such as material strengths, loadings, and environmental conditions. These estimates are used to develop probabilistic models that account for uncertainties associated with these parameters. These models are then integrated into reliability analysis methods, including probabilistic risk assessment (PRA) and reliability-based design, to evaluate structural performance and assess the probability of failure.

Moreover, data analysis techniques, such as statistical hypothesis testing, regression analysis, and survival analysis, enable to analyze failure data obtained from field observations or experiments. This analysis helps in understanding failure modes, identifying critical factors, and enhancing design and maintenance practices to improve the reliability of engineering structures.

3.3 DISTRIBUTION FUNCTIONS AND RANDOM VARIABLES

A probability distribution function (PDF), also referred to as a probability density function, is a mathematical function that characterizes the likelihood of various outcomes or values occurring within a random variable. It offers a probability measure for each possible value or range of values within a given probability distribution. The PDF describes the relative probabilities of different outcomes or values in a continuous random variable and provides information about the shape, spread, and other characteristics of the probability distribution. By integrating the PDF over a specific range, the probability of the random variable falling within that range can be determined.

There is always a link between a random variable (RV) and a set of parameters in every probability distribution function. The link between the random variable and the probabilities of its potential values or ranges is described by the probability distribution function. The discrete or continuous random process's numerical results are represented by the random variable. The distribution function's parameters control how it is shaped, where it is located, and how big it is, which has an impact on how the associated random variable behaves. We can learn more about the probabilities and behavior of the random variable by examining the probability distribution function and its parameters.

Conventionally, the PDF is denoted by a mathematical function, such as f(x), where x represents the potential values of the random variable. Different probability distributions, including the normal distribution, exponential distribution, and uniform distribution, have their own unique PDFs. The most important distributions used in practice are Normal, lognormal, uniform, Weibull, exponential, Gamma, Beta etc.

3.3.1 Normal Distribution Function

The normal distribution function, also referred to as the Gaussian distribution function, is a probability distribution that characterizes the likelihood of a continuous random variable assuming different values. It is recognized for its bell-shaped curve, exhibiting symmetry, and centered around its mean.

Parameters used are:

Mean Value of log (X) = μ

Standard Deviation of log (X) = σ

The expressions for μ and σ are given as in equation (3.1) and (3.2)

$$\mu = \int_{-\infty}^{\infty} x f(x) dx \tag{3.1}$$

$$\sigma = \sqrt{\int_{-\infty}^{\infty} (x - \mu)^2 f(x) dx} \tag{3.2}$$

The density function is given as in equation (3.3)

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[\frac{-1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right] \tag{3.3}$$

The cumulative distribution function is defined as in equation (3.4)

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{\infty} \exp\left[\frac{-1}{2}\left(\frac{v-\mu}{\sigma}\right)^2\right] dv \qquad (3.4)$$

The closed form solution of this integral does not exist. Therefore, an equivalent function Φ is formulated using the standard normal variable,

$$z = \frac{(x-\mu)}{\sigma}$$

$$\Phi(z) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{\frac{-u^2}{2}} du \qquad (3.5)$$

Φ(z) is the standard cumulative NDF. Values of this can be computed from different literatures. Fig 3.1 represents the pictorial representation of the density function. Fig 3.2 represents the Cumulative distribution function for the normal distribution with μ = 0

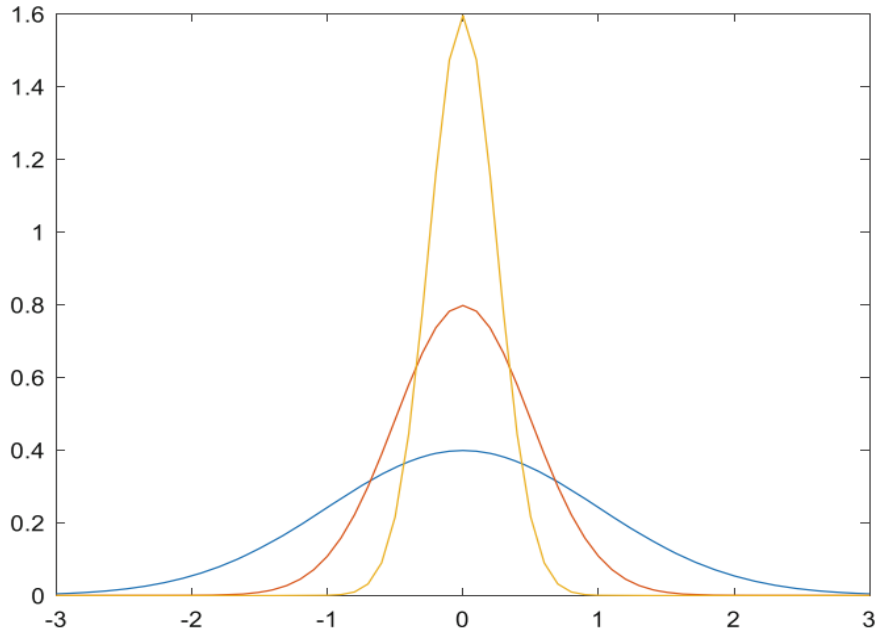


Fig.3.1 Normal distribution density with μ = 0 for different σ values.[10]

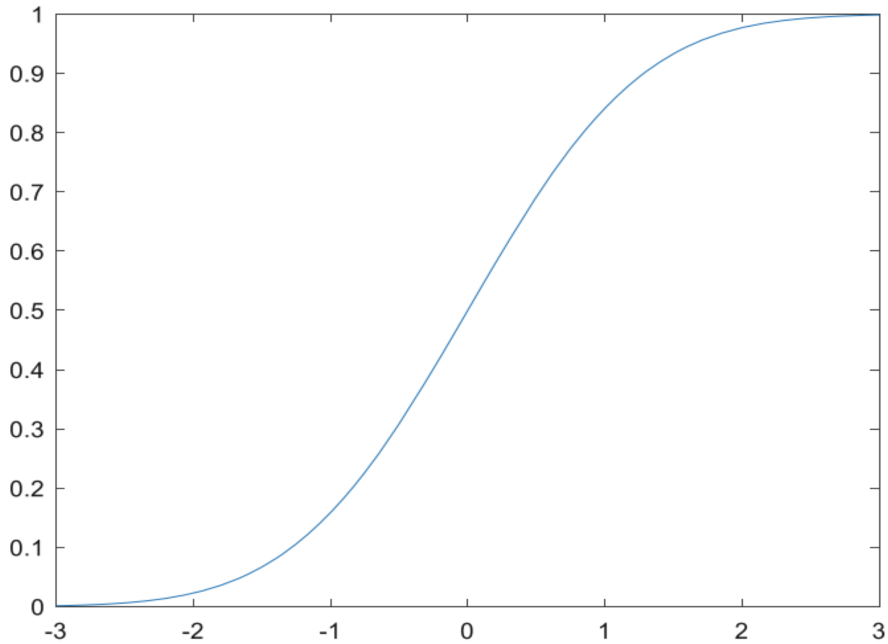


Fig. 3.2 Cumulative distribution function for the normal distribution with $\mu = 0$ [10]

3.3.2 Lognormal Distribution Function

The lognormal distribution is a probability distribution used to model random variables that are non-negative and exhibit exponential growth patterns. It is characterized by its skewed and asymmetric shape.

Parameters used are :

Mean of log(X) = λ

Standard Deviation of log (X) = ζ

The expressions for λ and ζ are given as in equation (3.6) and (3.7)

$$\lambda = \mathbf{E}\,(\ln x) \tag{3.6}$$

$$\zeta^2 = \ln\,(1 + \sigma^2/\mu^2) \tag{3.7}$$

The density function is expressed as

$$f(x) = \frac{1}{\zeta x\sqrt{2\pi}} \exp\left[\frac{-1}{2}\left(\frac{lnx - \lambda}{\zeta}\right)^2\right];\ 0 \leq x < \infty \qquad (3.8)$$

Fig.3.3 shows the pictorial representation of the density function.

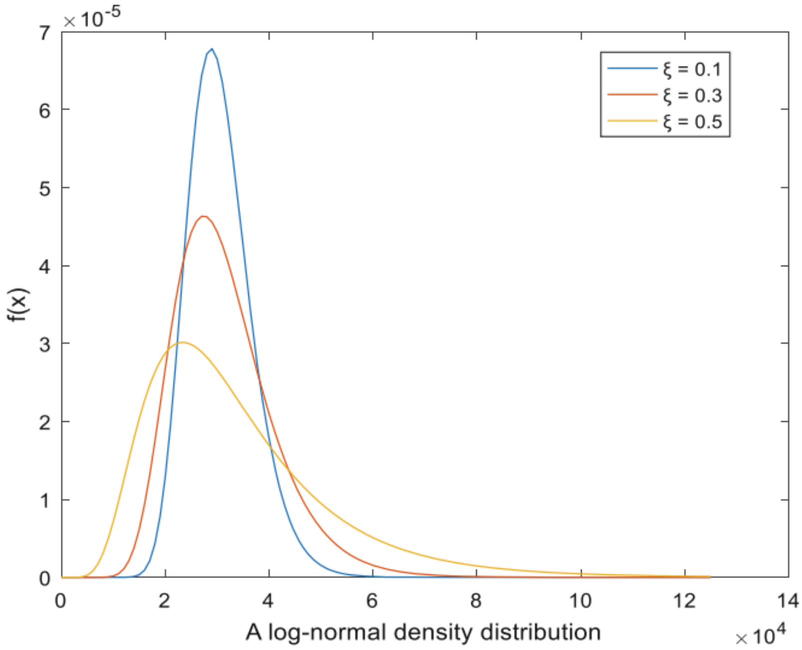


Fig.3.3 A log-normal density distribution [5]

3.3.3 Uniform Distribution

The uniform distribution, commonly known as the rectangle distribution, is a probability distribution that all values falling inside a given range for a continuous random variable are given equal probabilities. A constant probability density function (PDF) throughout the range is what defines it.

Parameters used are :

Lower end of uniform distribution = a

Upper end of uniform distribution = b

The density function is given as equation (3.9)

$$f(x) = f(x) = \begin{cases} \frac{1}{(b-a)}\ ; a \le x \le b \\ 0; \quad otherwise \end{cases} \tag{3.9}$$

Fig. 3.4 and Fig. 3.5 represent uniform distribution and density function respectively.

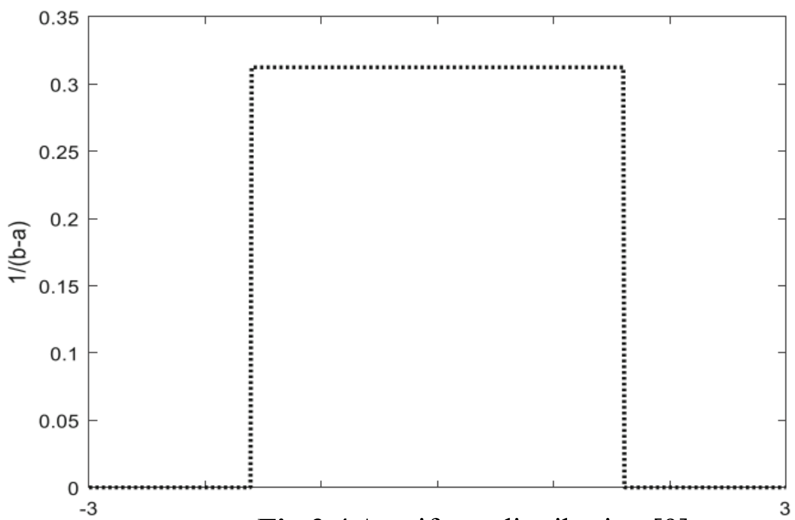


Fig.3.4 A uniform distribution [9]

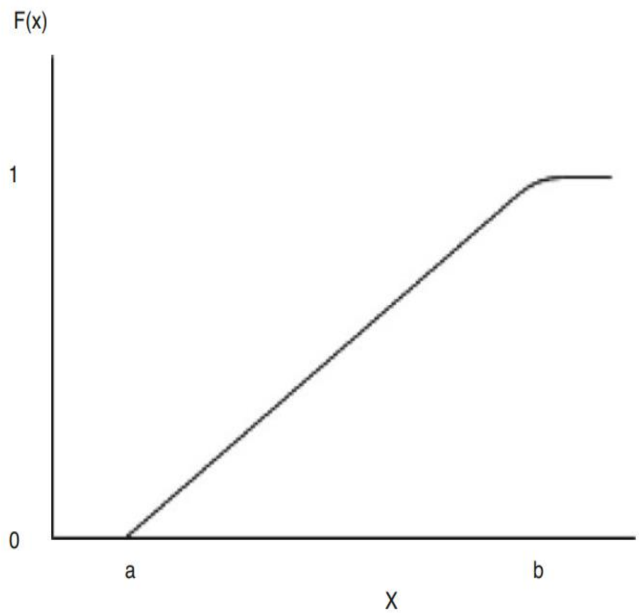


Fig.3.5 Uniform distribution density function [9]

3.3.4 Exponential Distribution

The failure rate is the only factor that distinguishes the exponential distribution. To simulate the interval between occurrences in a system or process, it is a statistical distribution that is frequently used in reliability analysis and other domains.

The failure rate in the exponential distribution denotes the typical rate at which failures or occurrences take place. Higher values of indicate a higher failure rate and shorter anticipated time between incidents. It impacts the shape and scale of the distribution curve.

The density function is expresses as

$$f(x) = \begin{cases} \lambda e^{-\lambda x}; & x \geq 0 \\ 0; & other\ value\ of\ x \end{cases} \tag{3.10}$$

Cumulative density function is expressed as

$$F(x) = \begin{cases} 1 - e^{-\lambda x}; & x \geq 0 \\ 0; & x < 0 \end{cases} \tag{3.11}$$

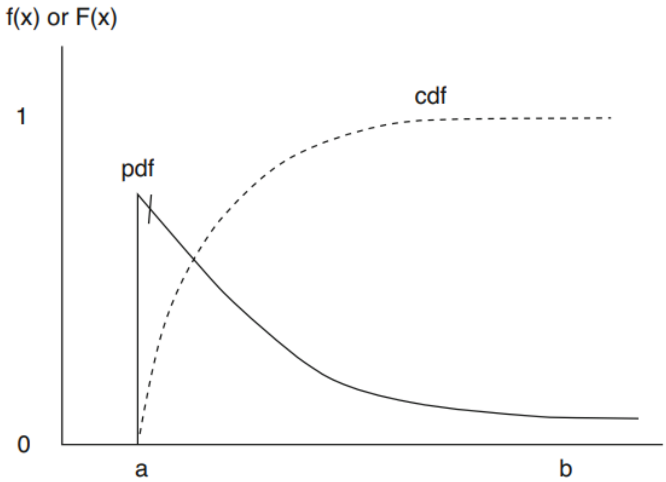


Fig. 3.6 Density function and CDF Plot [5]

3.3.5 Weibull Distribution

The Weibull distribution is a probability distribution extensively utilized to model the lifetime and reliability of systems or phenomena. Characterized by two parameters, the Weibull distribution offers flexibility in capturing different distribution shapes and scales. The shape parameter (k) determines the form of the distribution curve, while the scale parameter (λ) governs the spread or scale of the distribution. The Weibull distribution can exhibit a variety of shapes, including exponential, normal, and bathtub curves, based on the value of the shape parameter.

Parameters involved are :

Shape parameter = Ω

Scale parameter = ¥

The density function is given by

$$f(x) = -\frac{dR(t)}{dt} = \frac{\Omega}{¥}\left(\frac{t}{¥}\right)^{\Omega-1} e^{-\left(t/¥\right)^{\Omega}} \tag{3.12}$$

Fig.3.7 shows a Weibull distribution density function

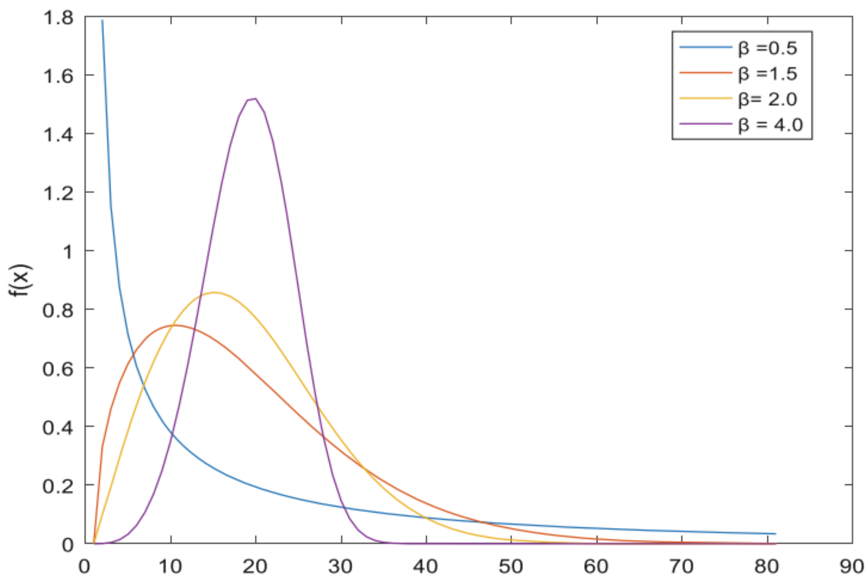


Fig.3.7 Weibull distribution density function [7]

CHAPTER-4

STRUCTURAL RELIABILITY

4.1 DEFINITION OF RELIABILITY

The likelihood that a system or component will effectively carry out a specific function for a predetermined amount of time when used under predetermined circumstances is referred to as reliability. Reliability is frequently defined in terms of the likelihood of a successful outcome. Reliability can be described in respect to a certain feature of an element to provide further clarity.

For instance, in the case of a structural element exposed to stress due to applied loads,

Reliability can be defined as

$$R = P[\text{Capacity (C)} > \text{Demand (D)}]$$

It is crucial to understand that applied loads or demand-related stress are both regarded as random variables, as are a system's strength, resistance, or capacity. The fact that the variables connected to the physical processes are regarded as random variables is essential to reliability analysis. In evaluating the reliability of a system or component, this assumption acknowledges the inherent unpredictability and uncertainty in these factors.

If the Resistance (R) and Stress (S) are considered to be normally distributed, as shown in Fig 4.1, the Reliability of system is defined as

$$R = 1 - P_f \tag{4.1}$$

Where P_f = Probability of failure, is expressed as

$$P_f = 1 - \Phi\left[\frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}}\right] \quad (4.2)$$

This equation (4.2) can be modified if the random variables are log-normally distributed as

$$P_f = 1 - \Phi\left[\frac{\ln\left[\frac{\mu_R}{\mu_S}\right]}{\sqrt{\delta_R^2 + \delta_S^2}}\right] \quad (4.3)$$

where

μ_R = mean value of Capacity or Resistance

μ_S = mean value of Demand or Stress

σ_R = Standard Deviation of Resistance or Capacity

σ_S = Standard Deviation of Demand or Stress

Φ = cumulative standard normal distribution function

δ = Coefficient of variation = $\frac{\text{standard deviation}}{\text{mean}}$

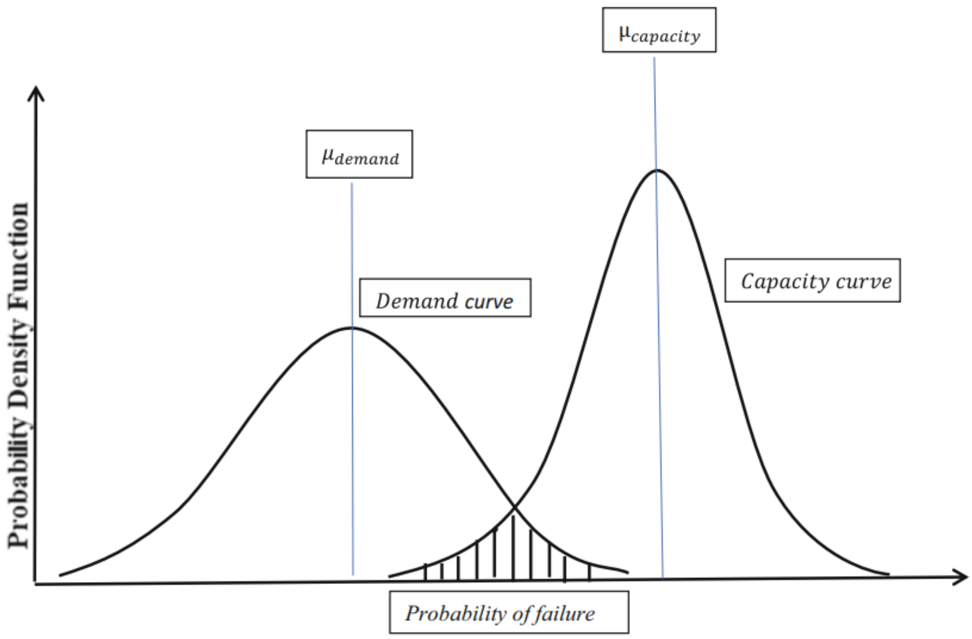


Fig.4.1 Fundamental Reliability Curve [1]

4.1.1 RISK

The ratio between the anticipated (mean) values of resistance and stress can be thought of as the deterministic counterpart of reliability. The link between the typical capacity or strength of a system (represented by resistance) and the typical intensity of applied loads or demands (represented by stress) is quantified by risk. Risk provides insight into the possibility of failure or the likelihood that the system would operate over its capacity under specific circumstances by comparing these mean values.

Risk analysis involves assessing the deterministic aspects of resistance and stress, considering their average values rather than accounting for the inherent variability and uncertainties associated with these variables. This deterministic approach simplifies the analysis by assuming that the mean values adequately represent the behavior of the system.

Equation (4.4) gives the mathematical definition of risk as

$$\text{Risk} = \frac{\mathrm{E(D)}}{E(C)} \text{ x (Severity)} \tag{4.4}$$

Severity values for structures pertain to the evaluation or categorization of the potential consequences associated with different types of structural failures. These values are determined based on the magnitude of potential harm or losses that could arise from such failures.

The process of determining severity values requires expertise, engineering analysis, and adherence to relevant codes and guidelines. Thorough assessments are conducted to accurately gauge the potential severity of failures and implement appropriate measures to mitigate risks and enhance structural safety.

4.1.2 Reliability Index

The reliability index is a numerical metric used in reliability analysis to evaluate the likelihood that a system or component will fall short of predefined performance standards. It represents a numerical number or probability that measures the level of reliability or the likelihood that an activity will succeed. Probabilistic models and statistical approaches are used to account for uncertainties related to system attributes and performance criteria in the computation of the reliability index. The probability distributions of pertinent variables, such as loads, strengths, and other elements influencing system performance, are considered while calculating the reliability index. To estimate the reliability index, these distributions are integrated using appropriate mathematical techniques, such as the First Order Reliability Method (FORM) or Monte Carlo simulation. It is denoted as β and expressed as

$$\beta = \left[\frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}}\right] \tag{4.5}$$

4.1.3 Reliability Factors

Resistance Factor : The resistance factor is a parameter employed in the design and analysis of structural or component systems. It is also referred to as the strength reduction factor, resistance coefficient, or safety factor. The resistance factor serves as an adjustment or reduction applied to the nominal or characteristic strength of a structural element or material. By reducing the design strength to a level that is expected to be consistently achievable in practice, the resistance factor ensures an appropriate level of safety and reliability. A higher resistance factor leads to a lower design strength and a greater margin of safety.

$$\text{Resistance Factor} = [1 - 0.75\ \beta\ (COV_R)] \tag{4.6}$$

Load Factor : The load factor represents a scaling factor applied to the anticipated or operating loads of a system or component. This adjustment accounts for uncertainties and variations inherent in the load conditions. By incorporating a load factor, the anticipated or nominal loads are increased to a higher level, providing a more conservative and reliable analysis.

$$\text{Load Factor} = [1 + 0.75\ \beta\ (COV_S)] \quad (4.7)$$

Another used factor is Central Safety Factor is the ratio of Load factor and Resistance Factor.

$$C.S.F = \frac{\text{Load Factor}}{\text{Resistance Factor}} \quad (4.8)$$

4.2 FRAMEWORK FOR RELIABILITY ANALYSIS

A framework for reliability analysis provides a structured approach to systematically evaluate and assess the reliability of systems or structures. The evaluation of a structure's safety is based on its performance as a whole or in specific parts, and it is typically described in relation to a defined set of limit states. These limit states distinguish between acceptable states, where the structure meets the required criteria, and unacceptable states, where it fails to meet those criteria. Different limit states include limit states of collapse, serviceability, shear, stress etc. A general reliability framework includes of the following components. Fig.4.2 shows the basic framework for reliability analysis

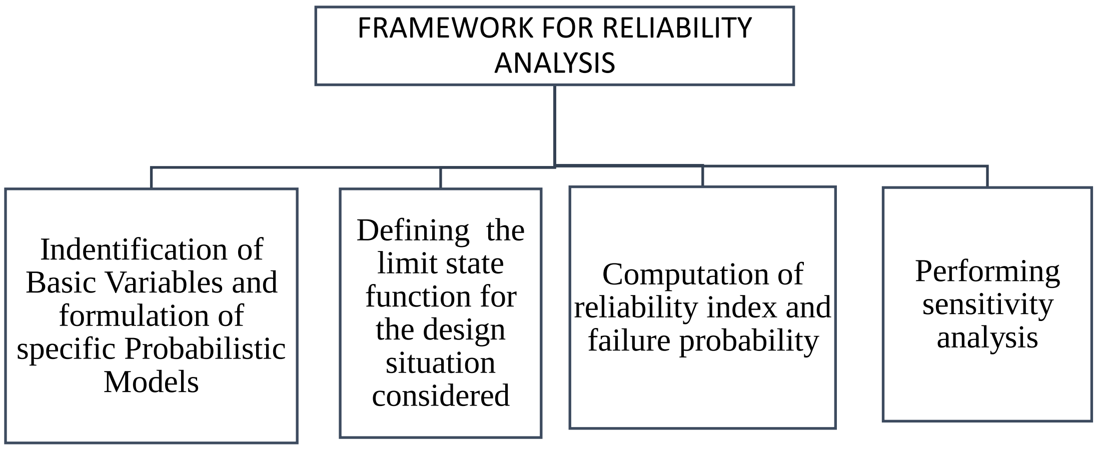


Fig.4.2 Basic Framework for Reliability Analysis

4.3 METHODS FOR RELIABILITY ANALYSIS

Methods of structural reliability encompass a range of techniques and approaches utilized to evaluate the safety and probability of failure of structures. These methods aim to address uncertainties, variations, and potential risks associated with structural behaviour and performance.

4.3.1 First Order Reliability Method

For determining the possibility of failure in systems or buildings, reliability analysis frequently use the First Order Reliability Method (FORM). It is an aspect of the Second Order Reliability Method (SORM), and it works especially well when working with linear limit-state functions and known or estimated input variable distributions. By converting the initial limit-state function into a regular normal space, FORM makes the analysis easier to understand. It simplifies the reliability calculations by assuming that the limit-state function can be represented by a linear surface in this space.

On the limit-state surface, the FORM algorithm first locates an initial design point where the probability of failure is anticipated to be significant. The direction of steepest ascent is then determined by computing a gradient of the limit-state function at this moment. The design point is then incrementally changed in this manner until convergence is reached. The distance between the design location and its location in the standard normal space is considered to evaluate the likelihood of failure. When dealing with extremely nonlinear limit-state functions, however, FORM's linear approximation may result in some degree of inaccuracy.

4.3.1.1 First Order Second Moment Method

By making a functional connection less complex, the FOSM method—also known as the Mean Value First Order Second Moment (MVFOSM)—offers a more straightforward way to determine the likelihood of failure. First-order expansion of the function is referred to as "first-order" in this sentence. Higher moments that represent distributional properties like skewness and kurtosis are ignored in favour of stating inputs and outputs as the mean and standard deviation. A first-order Taylor series expansion cantered around the mean value is used in the MVFOSM approach to approximate the limit-state function. This method allows for a more focused study while ignoring higher-order effects. Considering the Variables X as statistically independent, the limit state function at mean is defined as

$$g(X) = g(\mu_X) + \nabla g(\mu_X)^T (X_i - \mu_{Xi}) \tag{4.9}$$

$\mu_X = \{\mu_{X1,}\mu_{X2} \ldots\ldots \mu_{X2}\}^{\mathrm{T}}$ and $\nabla g(\mu_X)$ is gradient of g evaluated at μ_{X}

$$\nabla g(\mu_X) \;=\; \left\{\frac{\partial g(\mu_X)}{\partial x1}, \frac{\partial g(\mu_X)}{\partial x2}, \ldots\ldots, \frac{\partial g(\mu_X)}{\partial xn}\right\} \tag{4.10}$$

Mean Value of limit state function g(x) is given by

$$\mu_X = E[g(X)] = g(\mu_X) \tag{4.11}$$

Variance of function g(X) is given by

$$Var[g(X)] = Var[g(\mu_X)] + Var[\nabla g(\mu_X)^T (X_i - \mu_X)] \tag{4.12}$$

and standard deviation of g(x) is given by

$$\sigma_{g(x)} = \sqrt{Var[g(X)]} = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial g(\mu_x)^2}{\partial x_i}\right) \sigma_{x_i}^2} \tag{4.13}$$

Reliability Index β is given as

$$\beta = \frac{\mu_{g(X)}}{\sigma_{g(X)}} \tag{4.14}$$

The mean-value method is employed when dealing with nonlinear limit-state functions, where the approximate limit-state surface is derived by linearizing the original function at the mean value point. Hence, this approach is referred to as the mean-value method.

4.3.2 Second Order Reliability Method

A technique used in reliability analysis to estimate the risk of failure in systems with numerous variables and nonlinear limit-state functions is the second-order reliability method (SORM). By taking into account the curvature of the limit-state surface, SORM integrates second-order effects as opposed to the First-Order Reliability Method (FORM), which linearly approximates the limit-state function. Through a second-order Taylor series expansion cantered around the design point, SORM approximates the limit-state surface. Various statistical factors, including mean values, standard deviations, and correlations between the variables, are included in this expansion. By incorporating second-order moments and capturing the shape of the limit-state surface, SORM provides a more accurate estimation of the probability of failure compared to methods that solely rely on linear approximations.

When working with systems that have highly nonlinear limit-state functions and when the failure probability is low, SORM is especially useful. By considering higher-order effects and the collective behaviour of variables, it provides a more accurate assessment of system reliability.

Both FORM and SORM seek to determine the most likely point, which equates to the design element that increases the likelihood of failure.

Finding the precise location on the limit-state surface where the dependability index, frequently abbreviated as, equals a predetermined threshold value yields the most probable point in FORM. The difference in standard deviations between the design point and the mean of the limit-state function is represented by the dependability index. The goal of FORM is to identify the design point that meets the specified reliability level under the assumption that the limit-state function is approximated linearly.

SORM, in contrast, adds second order effects and takes into account the curvature of the limit-state surface. The reliability index, which takes into account both the mean values and the standard deviations of the input variables, is optimised in SORM in order to arrive at the most likely point. The accuracy of selecting the most likely point is increased by SORM's inclusion of higher-order moments, including the covariance and correlation between variables.

Both methods involve an iterative process of adjusting the design point until the desired reliability level is reached. However, SORM offers a more refined estimation by considering higher-order effects, resulting in a more precise determination of the most probable point compared to FORM.

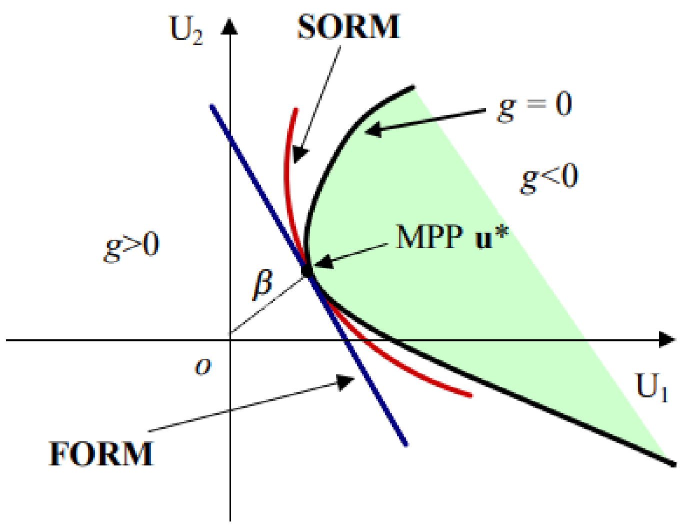


Fig.4.3 Comparison between FORM and SORM [16]

4.3.3 MONTE CARLO SIMULATION

The reliability of structures is frequently assessed using Monte Carlo simulation. It is a computational technique that evaluates the structure response by iteratively sampling input variables from their respective probability distributions. Statistics can be used to analyse uncertainty in structural engineering problems using Monte Carlo analysis. It works especially well in complicated situations when numerous random variables are related by nonlinear equations. Making a set of random numbers is the first step in a Monte Carlo study. These figures are produced mechanically or electronically. Fig.4.3 shows the framework for reliability analysis using Monte Carlo Simulation:

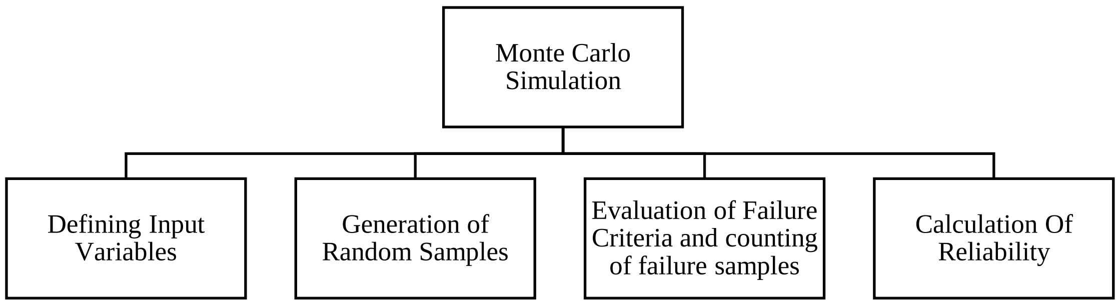


Fig.4.3 Framework for Monte Carlo Simulation

The above discussed methods have been discussed and used in the coming chapters to estimate the Reliability index and probability of Failure for the structural members. A comparison between the values of Reliability Index has been provided.

CHAPTER-5

RELIABILITY OF STRUCTURAL COMPONENTS

5.1 LIMIT STATE FUNCTION

Since they specify the standards for failure in structural engineering problems, limit state functions are essential to reliability estimates. These procedures establish the connection between the relevant input variables and the desired output variable. The different types of limit state functions commonly used in reliability calculations are:

Strength limit state: This function compares applied loads to the structural strength, ensuring that the structure can withstand the loads without exceeding its capacity. It considers factors such as material strength, safety margins, and design codes.

Serviceability limit state: Serviceability limit state functions focus on maintaining the structure's functionality under normal operating conditions. They establish criteria for acceptable deflections, vibrations, or crack widths to ensure the structure meets performance requirements.

Stability limit state: Stability limit state functions evaluate the stability of structures, considering factors like buckling and overturning. These functions address geometric imperfections, load distribution, and other relevant parameters to prevent instability and potential failure.

Fatigue limit state: Fatigue limit state functions address the accumulation of damage caused by cyclic loading over time. They incorporate variables such as load amplitudes, number of cycles, and material fatigue properties to ensure the structure can withstand repeated loading without experiencing fatigue failure.

The specific form and complexity of limit state functions depend on the characteristics of the problem, the type of structure or system under analysis, and the applicable design standards. Reliability calculations utilize these limit state functions to calculate the probability of failure and ensure the structure or system meets the required level of safety and reliability.

The Building Model considered in Chapter 6 consists of beam elements as ISLB200 (Indian Standard Low Weight Beam). Considering the beam to be simply supported, the Reliability Index and Probability of Failure, for different limit state has been computed manually by FOSM and other methods and the results are validated by Reliability software COMREL. The results are computed and compared.

5.2 RELIABILITY PROBLEM STATEMENT

A simply supported I- Beam ISLB200 has been considered as shown in Fig.5.1. The standard values are considered given in Table 5.1. parameters are computed Mean values are calculated from Characteristic Values and Standard Deviation by underestimating strength and overestimating the loads using equations (5.1) and (5.2) formulated using IS456:2000. FOSM has been used to compute the different parameters such as Reliability Index, Probability of Failure, etc.

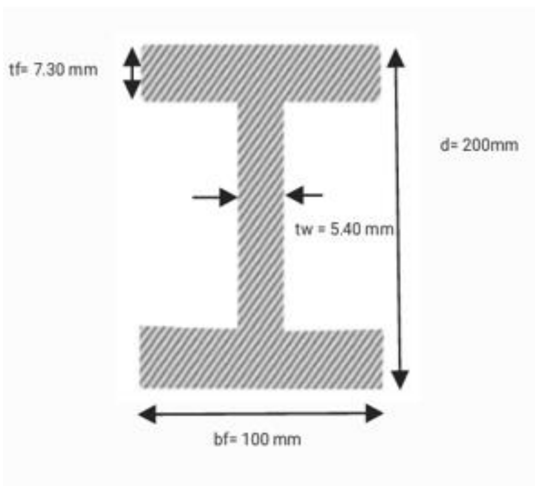


Fig.5.1 Sectional Properties of ISLB200

Table.5.1 Standard Values of Problem Statement Considering ISLB200

S.No	Variables	Characteristic Values	Coefficient of Variation	Mean Values	Standard Deviation
1	f_y(N/mm^2)	345	0.05	375.91	18.79
2	Z(mm^3)	1.697 x 10^5	0.05	1.849 x 10^5	9.245 x 10^{3}
3	W_D(N/mm)	0.198	0.05	0.182	9.147 x 10^{-3}
4	W_L(N/mm)	20	0.15	16.041	2.406
5	L(mm)	4000	0.05	4358.48	217.924
6	I_{xx}(mm^4)	0.16966 x 10^8	0.05	0.1848 x 10^8	0.924 x 10^6
7	y(mm)	100	0.05	108.96	5.448
8	τ_S(N/mm^2)	138	0.05	147.09	7.35
9	E (N/mm^2)	2.10 x 10^5	0.06	2.33 x 10^5	13.98 x 10^3
10	t_w(mm)	5.40	0.03	5.68	0.170
11	d(mm)	200	0.05	217.92	10.896
12	A(mm^2)	2527	0.05	2753.47	137.67

For strengths, mean value(μ),

$$\mu = \frac{x_{characteristic}}{1 - 1.645 \, . COV} \quad (5.1)$$

For Loads, mean value(μ),

$$\mu = \frac{x_{characteristic}}{1 + 1.645 \, . COV} \quad (5.2)$$

The limit state functions for different parameters are formulated and solved.

5.2.1 Strength Formulation

$$g(x) = R - S$$

The limit state function is defined by

$$g(x) = fy.Z - \frac{(WD + WL)L^2}{8} \qquad (5.3)$$

Resistance Parameter = *fy.Z*

Mean Value of Resistance Parameter = $\mu_R = (\mu_{fy}).(\mu_Z)$ = 69.50 e+6 N-mm

Similarly Mean Value of Stress Parameter = μ_S = 38.52 e+6 N-mm

Using equation (4.10), Partially differentiating R&S with respect to variables, mean values for individual 'R' and 'S' Parameters is determined.

$$\frac{\partial R}{\partial fy} = Z = \mu_Z = 1.849e+5$$

$$\frac{\partial R}{\partial Z} = fy = \mu_{fy} = 375.91$$

$$\frac{\partial S}{\partial W} = \frac{L^2}{8} = \frac{\mu_L^2}{8} = 2.374e+6$$

$$\frac{\partial S}{\partial L} = \frac{2W.L}{8} = \frac{\mu_W \cdot \mu_L}{8} = 17676.90$$

Standard Deviation Calculations can be made using equation (4.13). Using this equation, the combined value for standard deviations of 'R' and 'S' parameter is computed as σ_R= 4.913e+6 and σ_S= 6.88e+6

The reliability Index (β) is calculated using equation (4.5). By putting the values of parameters obtained in equation (4.5), β =3.66

5.2.1.1 Input Values In COMREL

Figures 5.2 To 5.17 Show the input parameters and the distribution and density plots for different parameters selected.

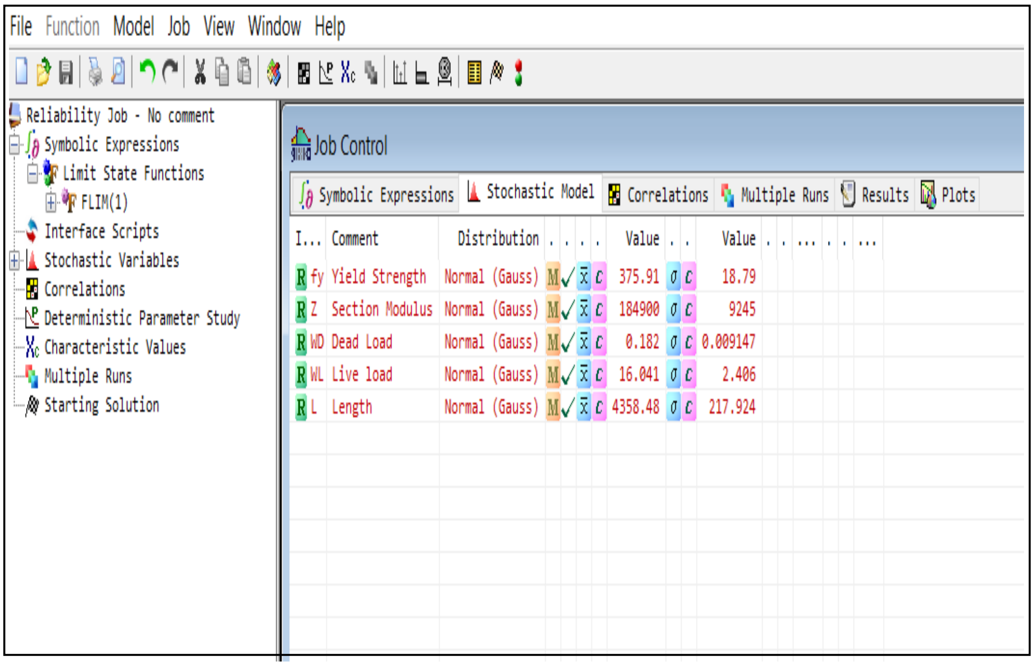


Fig.5.2 Input Values in COMREL for all parameters

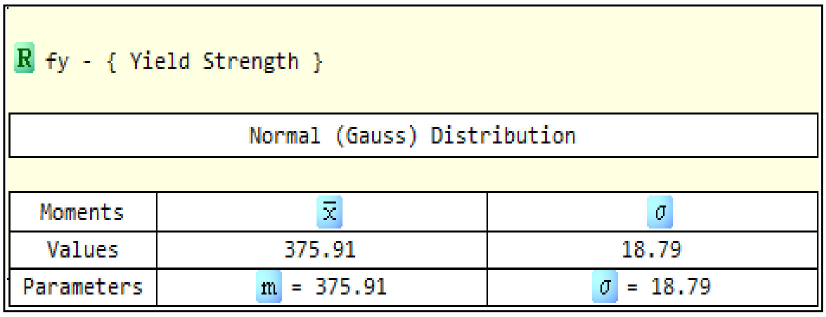


Fig.5.3 Input Values in COMREL for Yield Strength

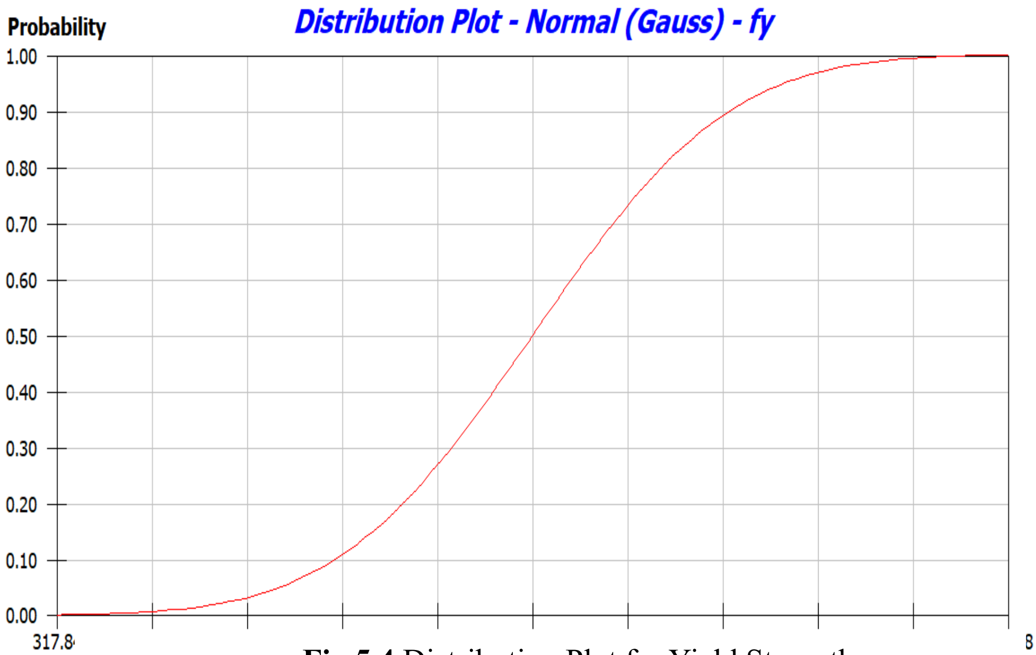


Fig.5.4 Distribution Plot for Yield Strength

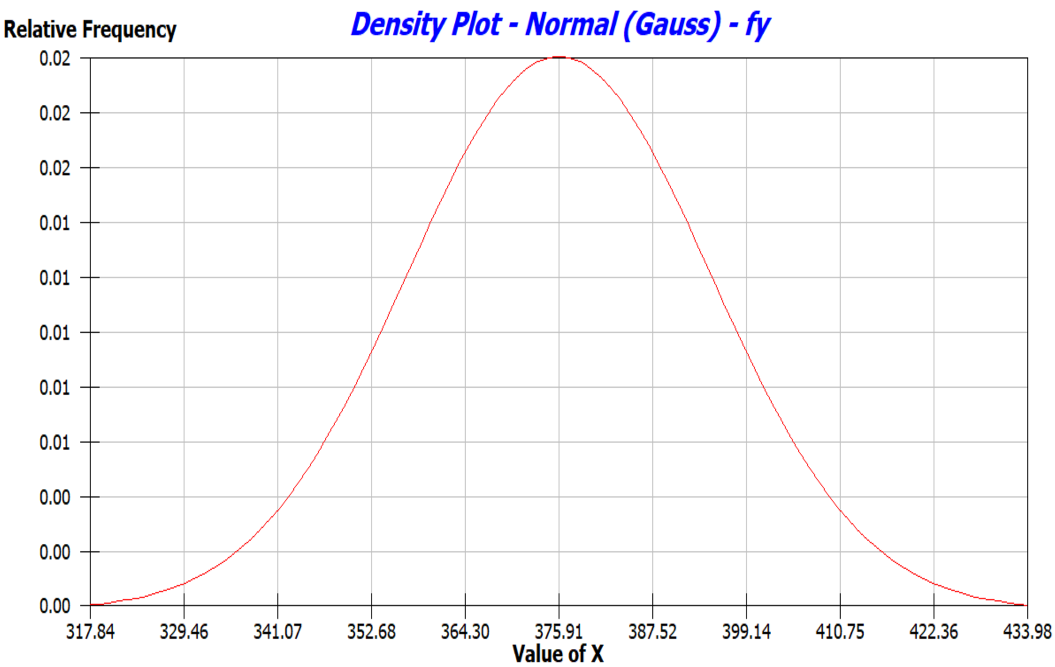
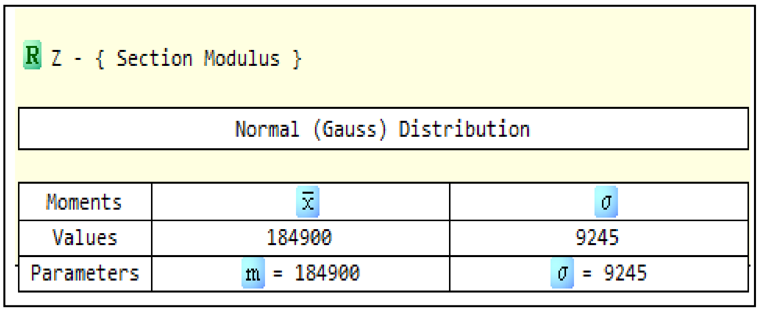


Fig.5.5 Density Plot for Yield Strength



Z - { Section Modulus }

Normal (Gauss) Distribution		
Moments	$\bar{x}$	σ
Values	184900	9245
Parameters	m = 184900	σ = 9245

Fig.5.6 Input Parameter Values for Section Modulus

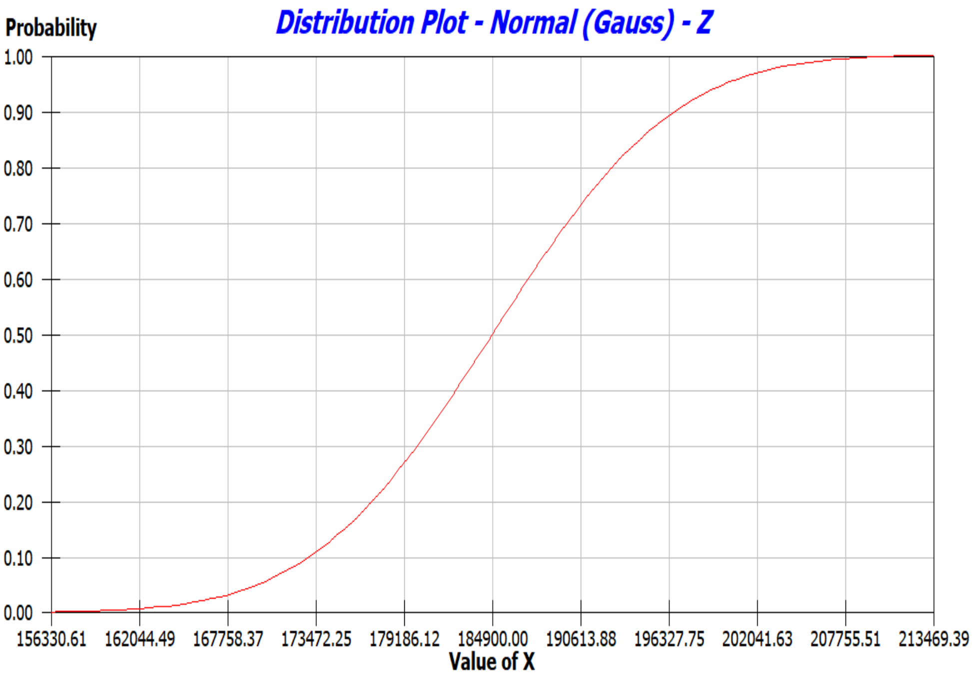


Fig.5.7 Distribution Plot for Section Modulus

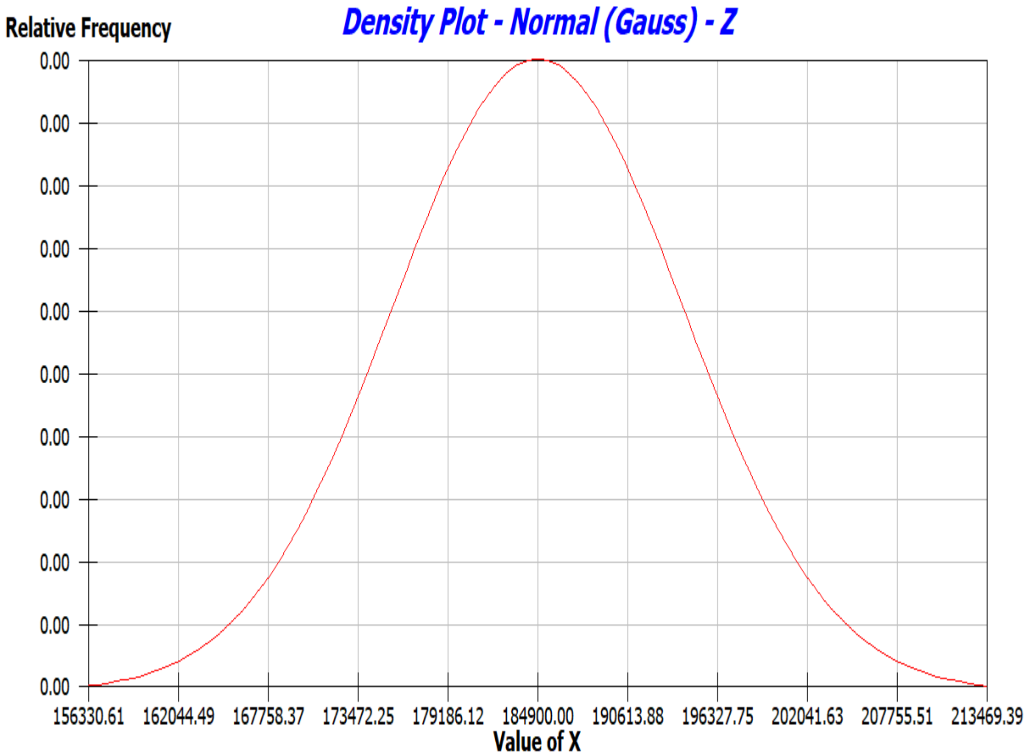
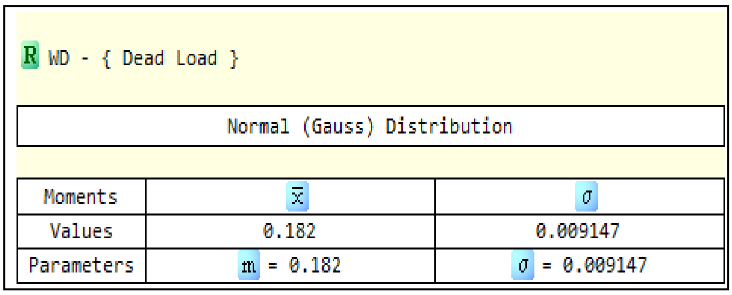


Fig.5.8 Density Plot for Section Modulus


R WD - { Dead Load }

Normal (Gauss) Distribution

Moments	$\bar{x}$	σ
Values	0.182	0.009147
Parameters	m = 0.182	σ = 0.009147

Fig.5.9 Input Parameter Values for Dead Load

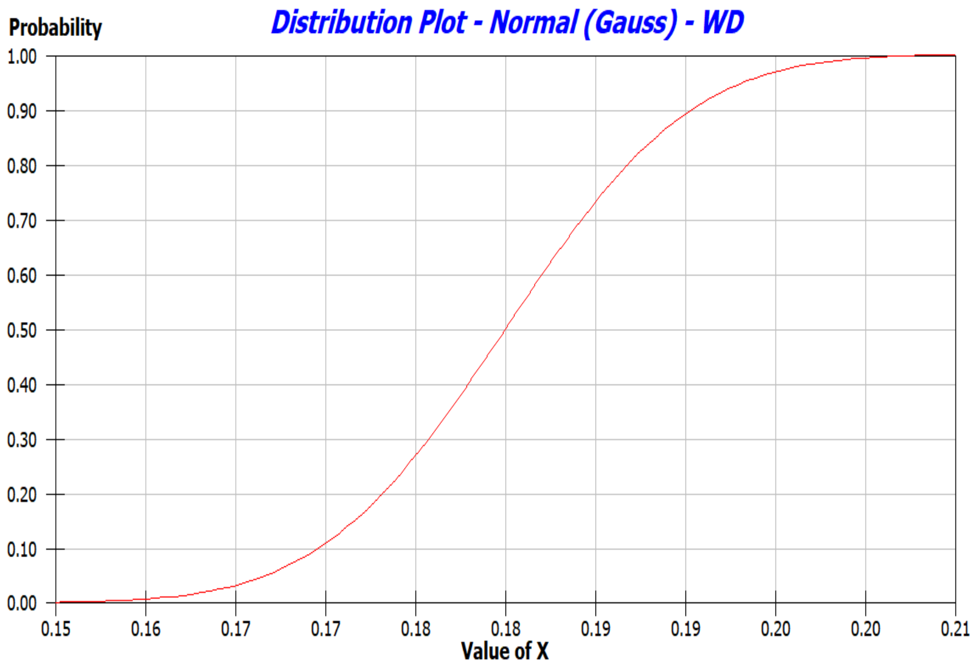


Fig.5.10 Distribution Plot for Dead Load

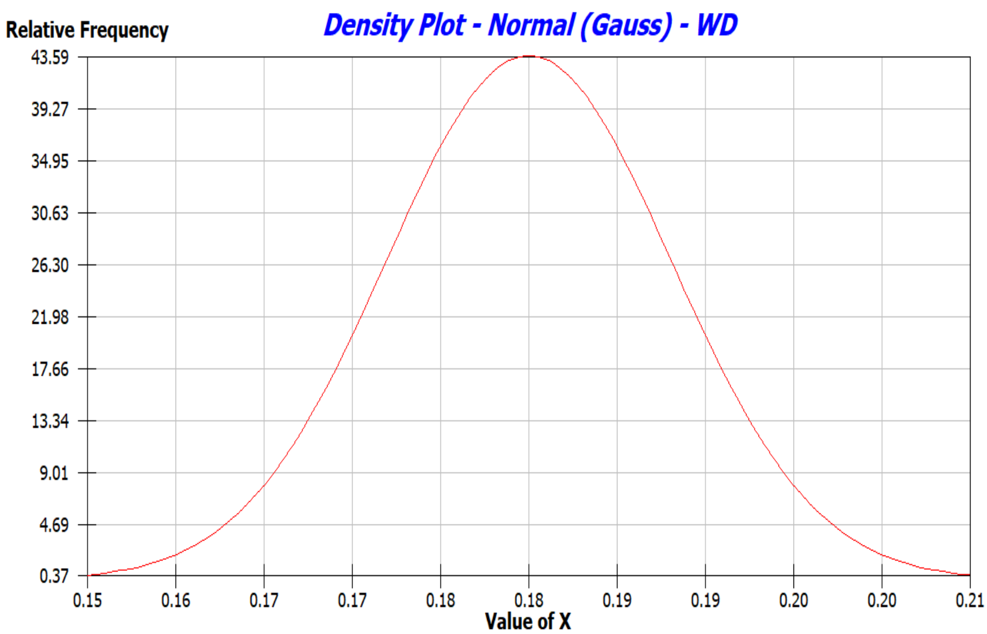


Fig.5.11 Density Plot for Dead Load

R WL - { Live Load }

Normal (Gauss) Distribution		
Moments	$\bar{x}$	σ
Values	16.041	2.406
Parameters	m = 16.041	σ = 2.406

Fig.5.12 Input Parameter Values for Live Load

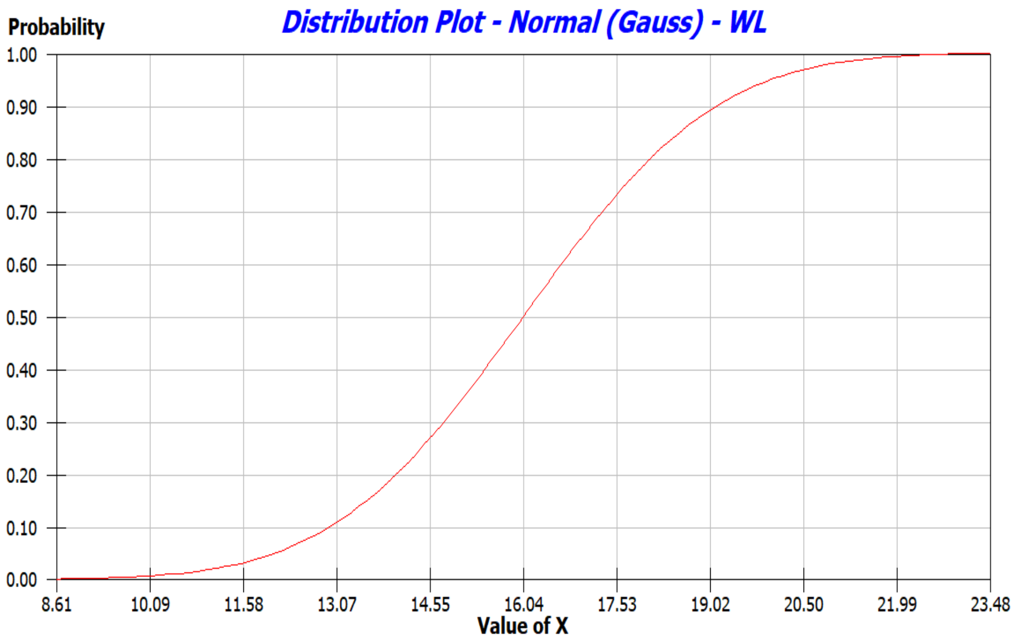


Fig.5.13 Distribution Plot for Live Load

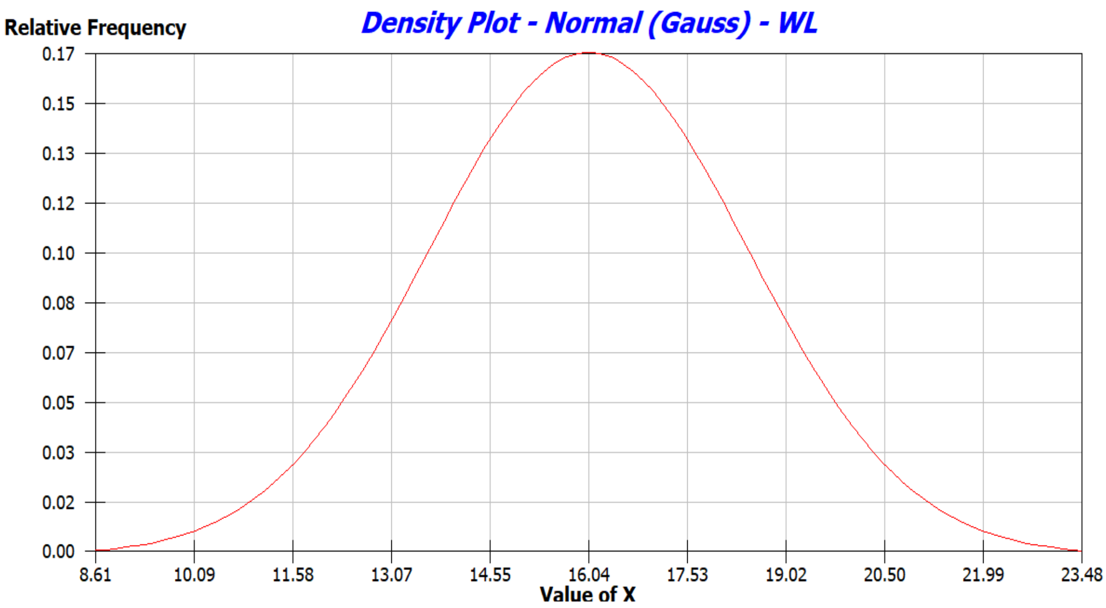


Fig.5.14 Density Plot for Live Load

R L - { Length }

Normal (Gauss) Distribution

Moments	$\bar{x}$	σ
Values	4358.48	217.924
Parameters	m = 4358.48	σ = 217.924

Fig.5.15. Input Parameter Values for Length of Beam

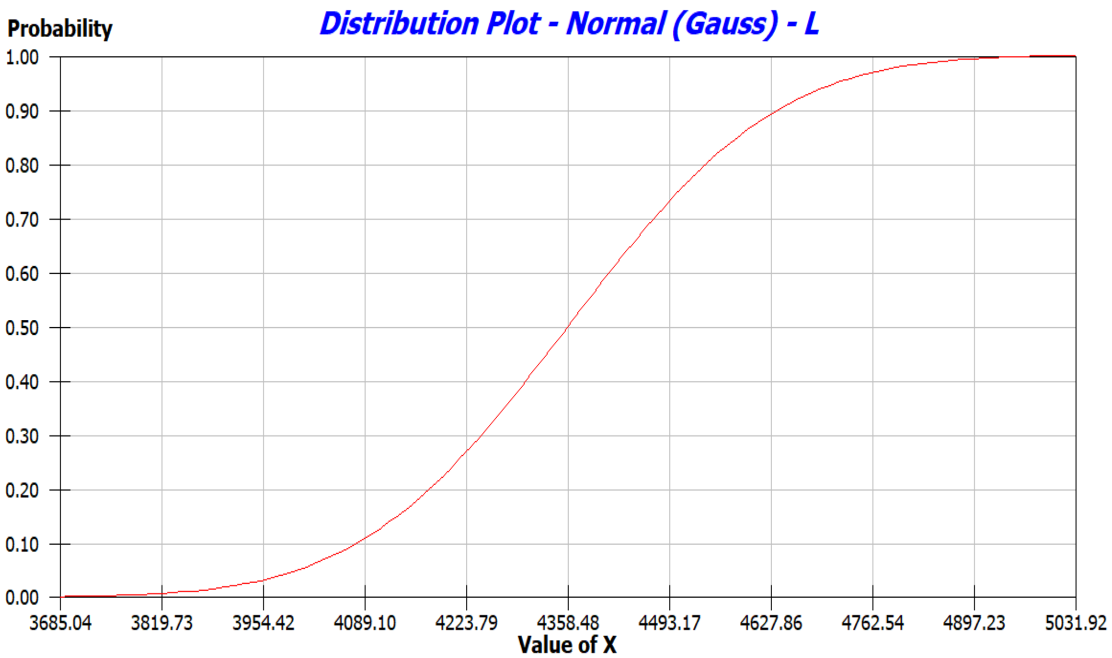


Fig.5.16 Distribution Plot for Length of Beam

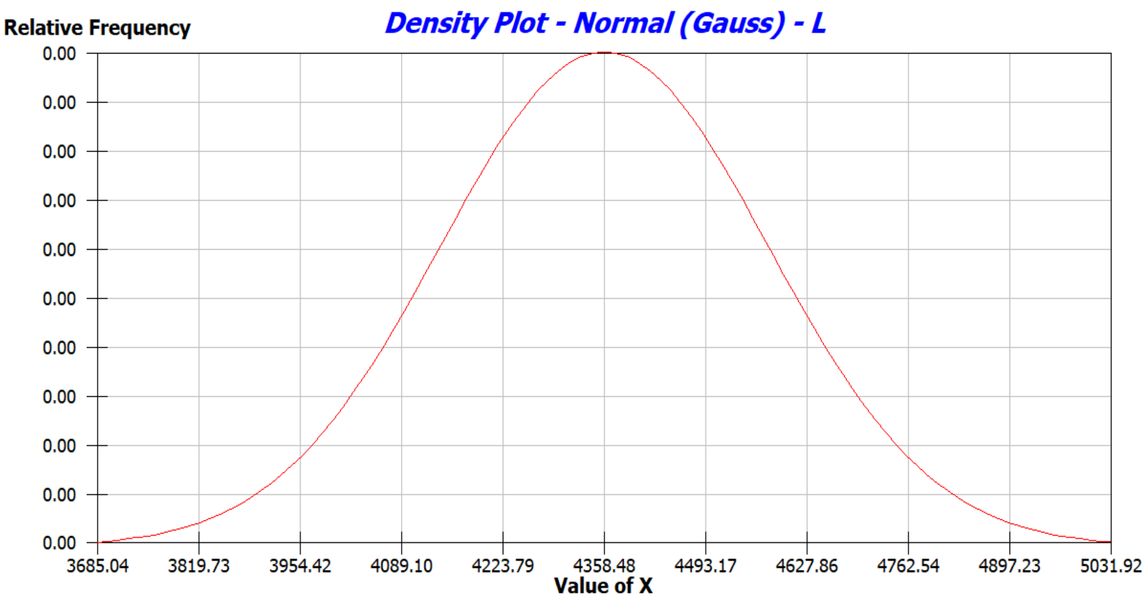


Fig.5.17 Density Plot for Length of Beam

5.2.1.2 Results In COMREL

```
              **********************************************
              --------- Comrel-TI (Version 2023) -----------
              ---- (c) Copyright: RCP GmbH (1989-2023) -----
              **********************************************

------------------------------------------------------------------------------
  Job name ............ :                                               DEMO
  Failure criterion no. :      1
  Comment : No comment
  Transformation type   : Rosenblatt
  Optimization algorithm: RFLS
------------------------------------------------------------------------------

 FORM-beta=   3.377; SORM-beta=   3.388; beta(Sampling)=   --     (IER=   0)
 FORM-Pf=  3.66E-04; SORM-Pf=  3.52E-04; Pf(Sampling)=    --

           --------- Statistics after COMREL-TI ---------
            State Function calls              =       52
            State Funct. gradient evaluations =     5
            Total computation time (CPU-secs.)=     0.02
            The error indicator (IER) was =    0
           **********************************************

 FLIM(1)    = 0.371928

 fy         = 355.146          Mean = 375.91          -5.5%
 Z          = 174681           Mean = 184900          -5.5%
 WD         = 0.18208          Mean = 0.182           +0.0%
 WL         = 21.5938          Mean = 16.041          +34.6%
 L          = 4774             Mean = 4358.48         +9.5%

Reliability analysis is finished
              --------- Comrel-TI (Version 2023) -----------
              ---- (c) Copyright: RCP GmbH (1989-2023) -----
              **********************************************

------------------------------------------------------------------------------
  Job name ............ :                                               DEMO
  Failure criterion no. :      1
  Comment : No comment
  Transformation type   : Rosenblatt
  Optimization algorithm: ------
------------------------------------------------------------------------------

 MVFO-beta=   3.661; SORM-beta=   --    ; beta(Sampling)=   --     (IER=   0)
 MVFO-Pf=  1.26E-04; SORM-Pf=    --     ; Pf(Sampling)=    --

           --------- Statistics after COMREL-TI ---------
            State Function calls              =        7
            State Funct. gradient evaluations =     1
            Total computation time (CPU-secs.)=     0.01
            The error indicator (IER) was =    0
           **********************************************

 FLIM(1)    = 3.09835e+07

 fy         = 375.91           Mean = 375.91          +0.0%
 Z          = 184900           Mean = 184900          +0.0%
 WD         = 0.182            Mean = 0.182           +0.0%
 WL         = 16.041           Mean = 16.041          +0.0%
 L          = 4358.48          Mean = 4358.48         +0.0%

Reliability analysis is finished.
```

```
---------------------------------------------------------------------------------
  Job name ........... : DEMO
  Failure criterion no. :      1
  Comment : No comment
  Transformation type   : Rosenblatt
  Optimization algorithm: RFLS
  Date(dd.mm.yyyy) .... : 10.05.2023
  Time(hh:mm) ........  : 17:52
  Comrel-TI, (Version 2023), Copyright: RCP GmbH (1989-2023)
---------------------------------------------------------------------------------

 Block beginning with Keyword $CHARVAL not found in Input-file !
 Characteristic Values default to mean values.

 Create buffer for $LIMFUNC with      3340 Bytes (Ier from Fstat =   0)

    ----------------------------------------
                  COMREL-TI
    Iteration monitoring of YBETAU algorithm
    ----------------------------------------
       General enviroment information
       Maximal number of iterations in RFLS1 =     50
       Maximal number of iterations in RFLS2 =     50
       Type of numerical derivatives         =      0
       Precision for convergence criteria    =   1.0000E-03
       Line search precision                 =   1.0000E-01

    Initial U-space solution
          0.0000      0.0000      0.0000      0.0000      0.0000

    Algorithm 1 : Iteration history
---------------------------------------------------------------------------------
 Iteration No.  1; CPU-seconds(cumulative):     0.004
  Scaled St.F(U) = -0.7506E-01; BETA =      0.0000; BETA/||U||=      0.0000
---------------------------------------------------------------------------------
 Iteration No.  2; CPU-seconds(cumulative):     0.004
  Scaled St.F(U) =  0.1660E-02; BETA =      3.6071; BETA/||U||=      1.0696
---------------------------------------------------------------------------------
 Iteration No.  3; CPU-seconds(cumulative):     0.004
  Scaled St.F(U) =  0.1774E-04; BETA =      3.3720; BETA/||U||=      0.9985
---------------------------------------------------------------------------------
 Iteration No.  4; CPU-seconds(cumulative):     0.004
  Scaled St.F(U) =  0.4471E-06; BETA =      3.3771; BETA/||U||=      1.0000
---------------------------------------------------------------------------------
 Iteration No.  5; CPU-seconds(cumulative):     0.008
  Scaled St.F(U) =  0.1200E-07; BETA =      3.3772; BETA/||U||=      1.0000
  Statistics after RFLS-algorithm #1 (YRFLS1)
  Cumulative seconds used        :       0.0078
  Number of iterations           :      5
  Cumulative gradient calls      :      5
  Cumulative state function calls:     31
  State function scaling         :   3.0984E+07

  Statistics after beta-point search :
  Cumulative seconds used        :       0.0078
  Number of iterations(RFLS-1+-2):      5
  Cumulative gradient calls      :      5
  Cumulative state function calls:     31

Second-Order Improvement; radii of curvature in U-space :
     -20.593-9999999.000     231.916      57.743
Chi**2 probability             =  4.3496E-02 (must be > SORM Pf)
SORM corrected Pf (Hohenbichler)=  3.5158E-04
Final SORM improved Pf         =  3.5158E-04
Equivalent SORM-beta (SORMBE)  =    3.3884

------------------ Results of Second-Order improvement------------------
Second-Order reliability index =   3.388
Corresponding prob. of failure = 3.51582E-04


  Transfer to GUI: NBV=   5;  NPVEC=   0

  -----Vector U-mem plus FU at solution                  -----
    -1.105         -1.105         0.8774E-02      2.308          1.907
    0.1200E-07

  -----Vector X at solution transfered to GUI            -----
     355.1          0.1747E+06     0.1821         21.59          4774.

  -----Vector of constant Parameters transfered to GUI   -----


  beta-value to GUI:      3.3884;  Pf-value to GUI:  3.5158E-04
```

5.2.1.3 Influence Coefficients and Partial Safety Factors

Influence coefficients: The absolute values of influence coefficients express how sensitive the problem is to each of the random variables. If the influence coefficient is positive, the associated random variable is of the 'Capacity' Type meaning the reliability increases if the mean of the random variable is increased. If the influence coefficient is negative, the variable is of the 'Demand' type. Consequently, the reliability decreases if the mean of the random variable is increased. The sum of the squares of influence coefficients is 1.

Partial Safety Factors for the problem for each of the selected characteristic values. By default, characteristic value is taken as mean value in COMREL.

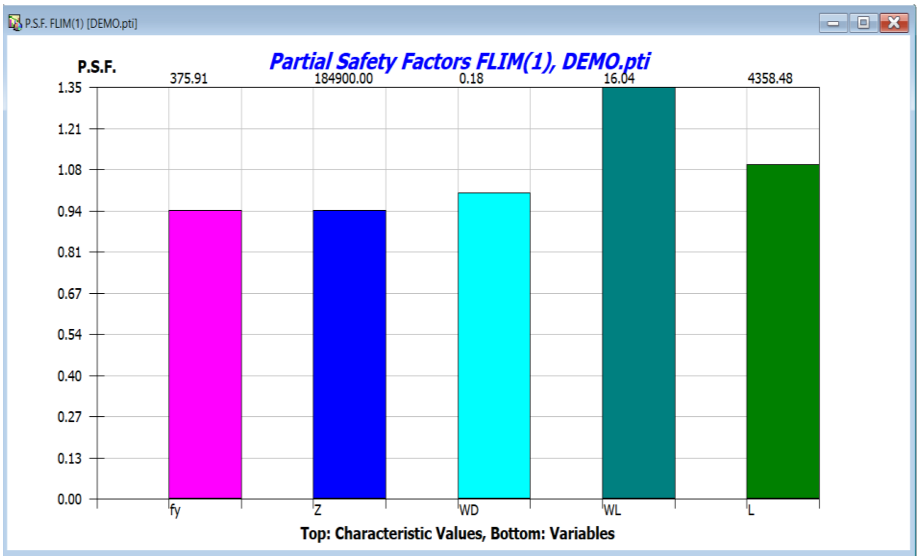


Fig.5.18 Partial Safety Factors

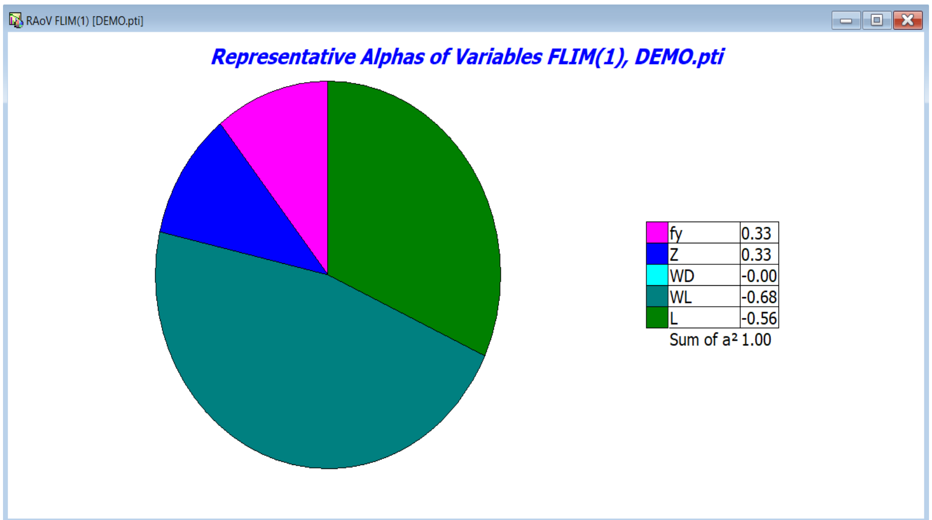


Fig.5.19 Influence Coefficients

5.2.2 Stress Formulation

The limit state function for stress formulation is computed as

$$g(x) = fy - \frac{M}{I}y \tag{5.4}$$

Table 5.2 summarizes the values obtained from calculations.

Table 5.2 Calculated Values for Limit State of Stress

Mean Value of Resistance Parameter (μ_R)	Mean Value of Strength Parameter (μ_S)	Standard Deviation Calculations		Reliability Index	Resistance Factor	Load Factor	Central Safety Factor
		σ_R	σ_S				
375.91	227.131	18.79	43.68	3.128	0.8850	1.45	1.63

5.2.2.1 Results in COMREL

```
**************************************************
--------- Comrel-TI (Version 2023) -----------
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**************************************************

------------------------------------------------------------------------------
 Job name ............ :
 Failure criterion no. :       1
 Comment : No comment
 Transformation type    : Rosenblatt
 Optimization algorithm: RFLS
------------------------------------------------------------------------------

 FORM-beta=   3.129; SORM-beta=   3.129; beta(Sampling)=   --    (IER=   0)
 FORM-Pf=  8.77E-04; SORM-Pf=  8.77E-04; Pf(Sampling)=    --

           --------- Statistics after COMREL-TI ---------
            State Function calls                =      14
            State Funct. gradient evaluations =     2
            Total computation time (CPU-secs.)=     0.02
            The error indicator (IER) was =     0
           **********************************************

 FLIM(1)     = -9.6266e-08

 R           = 352.678           Mean = 375.91          -6.2%
 S           = 352.678           Mean = 227.131         +55.3%

Reliability analysis is finished
```

5.2.3 Shear Formulation

The limit state function for stress formulation is computed as

$$g(x) = \tau_S t_w d - 0.5(WD + WL)L \quad (5.5)$$

Table 5.3 summarizes the values obtained from calculations.

Table.5.3 Calculated Values for limit state of shear

Mean Value of Resistance Parameter (μ_R)	Mean Value of Strength Parameter (μ_S)	Standard Deviation Calculations		Reliability Index	Resistance Factor	Load Factor	Central Safety Factor
		σ_R	σ_S				
182.06e+3	35.35e+3	0.0139 e+6	5533.20	9.760	0.441	2.14	4.852

5.2.3.1 Results in COMREL

```
            ***********************************************
            --------- Comrel-TI (Version 2023) -----------
            ---- (c) Copyright: RCP GmbH (1989-2023) -----
            ***********************************************

----------------------------------------------------------------------------
  Job name ........... :                                                DEMO
  Failure criterion no. :       1
  Comment : No comment
  Transformation type    : Rosenblatt
  Optimization algorithm: RFLS
----------------------------------------------------------------------------

 FORM-beta=   9.806; SORM-beta=   9.806; beta(Sampling)=   --    (IER=   0)
 FORM-Pf=  5.39E-23; SORM-Pf=  5.39E-23; Pf(Sampling)=    --

            --------- Statistics after COMREL-TI ---------
             State Function calls             =       14
             State Funct. gradient evaluations =     2
             Total computation time (CPU-secs.)=     0.01
             The error indicator (IER) was =     0
            **********************************************

 FLIM(1)    = -0.000224919

 R          = 55417.9          Mean = 182060          -69.6%
 S          = 55417.9          Mean = 35350           +56.8%

Reliability analysis is finished
```

5.2.4 Serviceability Formulation

The limit state function for stress formulation is computed as

$$g(x) = \frac{L}{360} - \frac{5WL^4}{384EI} \tag{5.6}$$

.

Table.5.4 Calculated Values for limit state of serviceability

Mean Value of Resistance Parameter (μ_R)	Mean Value of Strength Parameter (μ_S)	Standard Deviation Calculations		Reliability Index	Resistance Factor	Load Factor	Central Safety Factor
		σ_R	σ_S				
12.10	17.70	0.603	4.61	-1.204	1.004	0.260	0.732

5.2.4.1 Results in COMREL

```
                **********************************************
                --------- Comrel-TI (Version 2023) -----------
                ---- (c) Copyright: RCP GmbH (1989-2023) -----
                **********************************************

------------------------------------------------------------------------------
  Job name ............ :                                                DEMO
  Failure criterion no. :      1
  Comment : No comment
  Transformation type   : Rosenblatt
  Optimization algorithm: RFLS
------------------------------------------------------------------------------

 FORM-beta=  -1.204; SORM-beta=  -1.204; beta(Sampling)=   --    (IER=   0)
 FORM-Pf=  0.89    ; SORM-Pf=  0.89    ; Pf(Sampling)=    --

            --------- Statistics after COMREL-TI ---------
             State Function calls            =       13
             State Funct. gradient evaluations =     2
             Total computation time (CPU-secs.)=     0.03
             The error indicator (IER) was =    0
            **********************************************

 FLIM(1)    = 1.77636e-15

 R          = 12.1942          Mean = 12.1           +0.8%
 S          = 12.1942          Mean = 17.7           -31.1%

Reliability analysis is finished
```

5.3 Comparison between different Methods

The problem statement in **5.2** has been solved by using different methods. Table 5.5 shows the different values of Reliability Index and Probability of Failure at different limit states.

Table.5.5 Comparison between different Methods

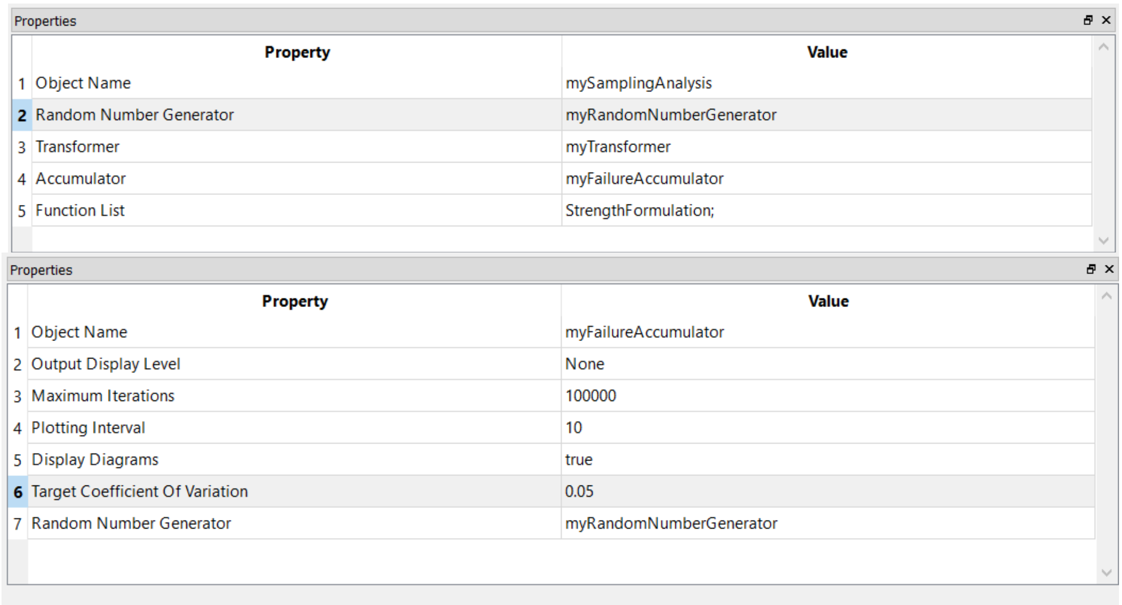
METHODS	FORM		SORM		MVFO	
LIMIT STATES	β	P_f	β	P_f	β	P_f
STRENGTH	3.377	3.66e-4	3.388	3.52e-4	3.661	1.26e-4
STRESS	3.129	8.77e-4	3.129	8.77e-4	3.128	8.79e-4
SERVICEABILITY	-1.204	0.89	-1.204	0.89	-1.341	0.91
SHEAR	9.80	5.39e-23	9.80	5.39e-23	9.760	8.49e-23

For various limit states, the Reliability Index displays a range of values. There can never be a negative reliability index. The traditional definition of the reliability index is the ratio of the random variable's standard deviation to the separation between the mean and the limit state function. The reliability index is always a non-negative number because both the mean value and the standard deviation are non-negative numbers. A positive value suggests a safe design with an adequate margin of safety because it shows that the mean value is greater than the limit state function. The mean value would be smaller than the limit state function if the reliability index were negative, suggesting an unsafe design condition, and zero would imply that the mean value exactly coincides with the limit state function. The maximum chance of failure is indicated by the fact that the reliability index calculated for the limit state of serviceability is negative.

5.4 RELIABILITY INDEX BY MONTE-CARLO SAMPLING

Reliability estimation utilizing Monte Carlo sampling is a prevalent technique employed in the field of reliability engineering. Monte Carlo sampling is a statistical method that involves generating random samples from probability distributions to estimate unknown parameters or analyze intricate systems.

The analysis is done using a program 'Rt' using an orchestrating algorithm for Sampling Analysis. The samples are processed by Failure Probability Accumulator. Maximum numbers of samples are taken as 1 lakh and a target COV as 5%. The different limit state functions are programmed and the plots for Failure Accumulator and Histograms are obtained along with output Results.


Properties

	Property	Value
1	Object Name	mySamplingAnalysis
2	Random Number Generator	myRandomNumberGenerator
3	Transformer	myTransformer
4	Accumulator	myFailureAccumulator
5	Function List	StrengthFormulation;

Properties

	Property	Value
1	Object Name	myFailureAccumulator
2	Output Display Level	None
3	Maximum Iterations	100000
4	Plotting Interval	10
5	Display Diagrams	true
6	Target Coefficient Of Variation	0.05
7	Random Number Generator	myRandomNumberGenerator

Figure 5.20 Command Assignment in Rt Software

5.4.1 Monte-Carlo Sampling for Strength Formulation

The formulated limit state function in **5.2.1** given by equation (5.3) is programmed in Rt software. The failure accumulator plot and histogram failure plot and output file are shown in Fig.5.21,Fig.5.22 and Fig.5.23 respectively.

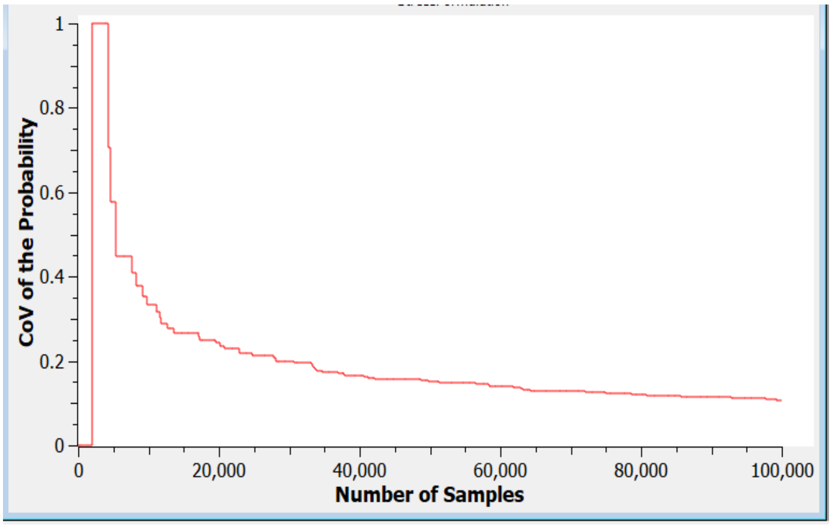


Figure 5.21 Failure Accumulator Plot for Strength Formulation

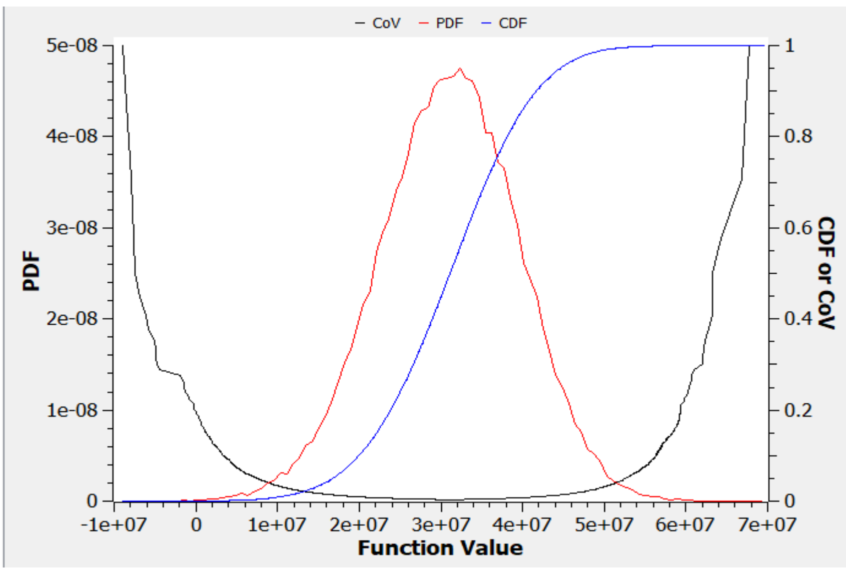


Figure 5.22 Histogram Failure Plot for Strength Formulation

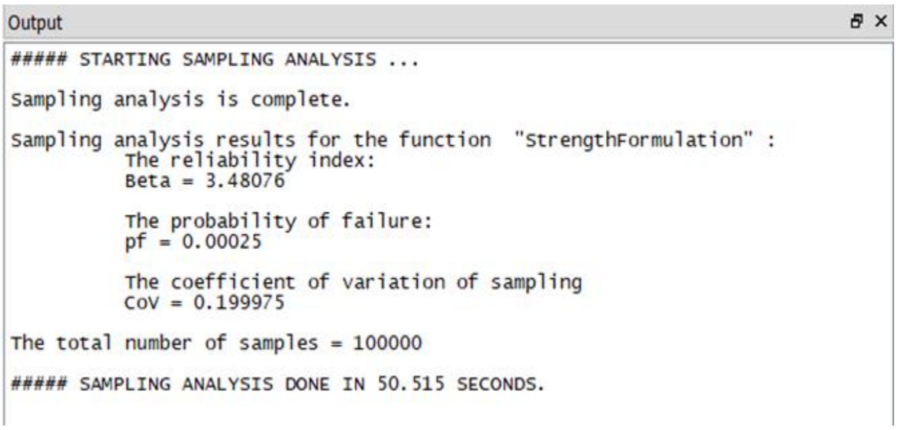


Figure 5.23 Output Results for Strength Formulation

5.4.2 Monte-Carlo Sampling for Stress Formulation

The formulated limit state function in **5.2.2** given by equation (5.4) is programmed in Rt software. The failure accumulator plot and histogram failure plot and output file are shown in Fig.5.24, Fig.5.25 and Fig.5.26 respectively.

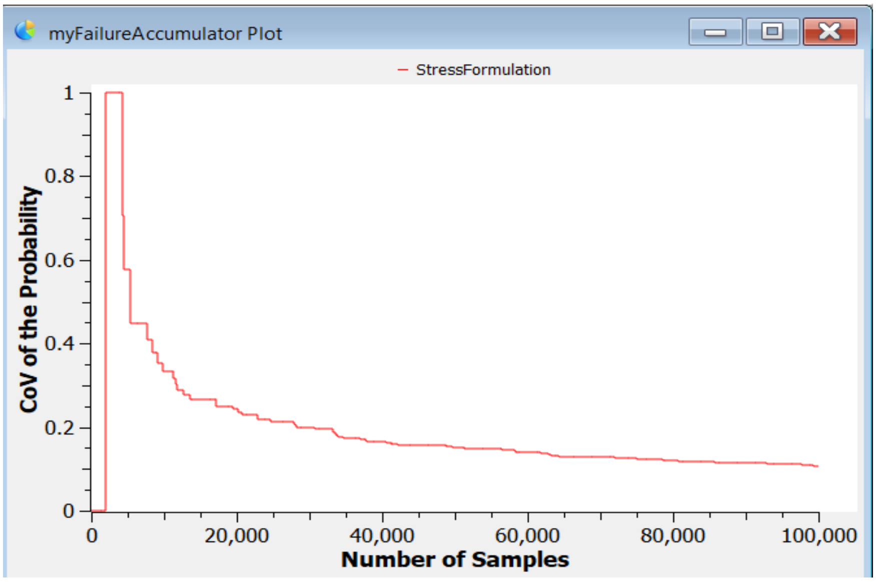


Figure 5.24 Failure Accumulator Plot for Stress Formulation

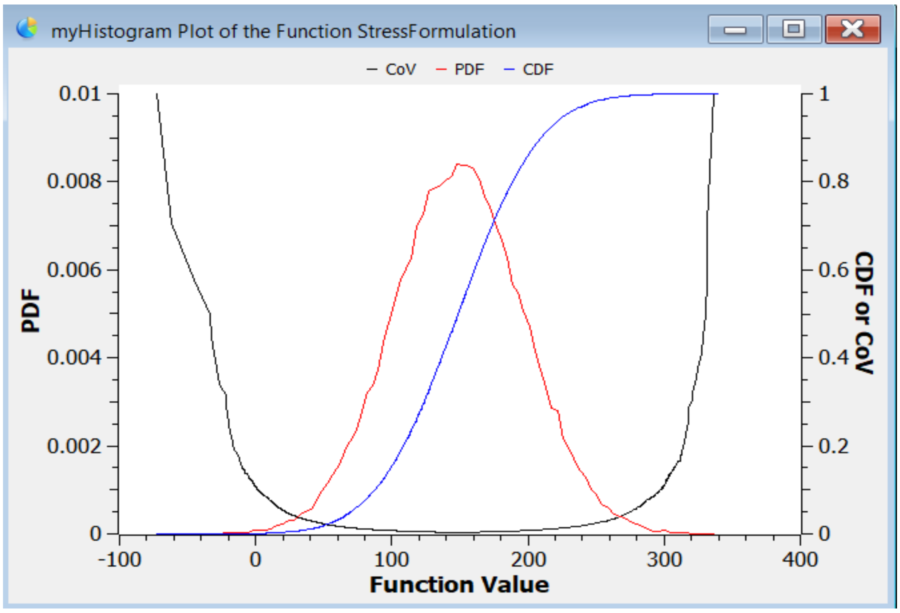


Figure 5.25 Histogram Failure Plot for Stress Formulation

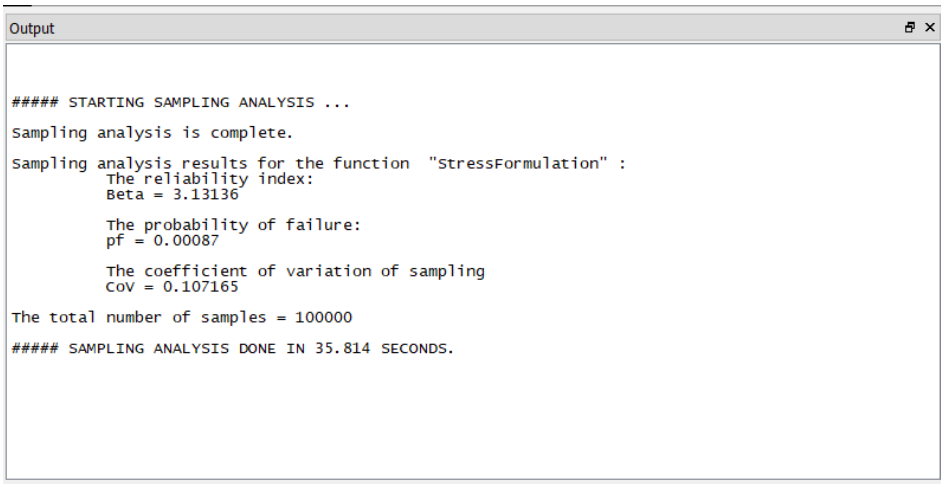


Figure 5.26 Output Results for Stress Formulation

5.4.3 Monte-Carlo Sampling for Serviceability Formulation

The formulated limit state function in **5.2.4** given by equation (5.6) is programmed in Rt software. The failure accumulator plot and histogram failure plot and output file are shown in Fig.5.17, Fig.5.28 and Fig.5.29 respectively. The probability of failure in this case comes out to be 90% as shown in output file.

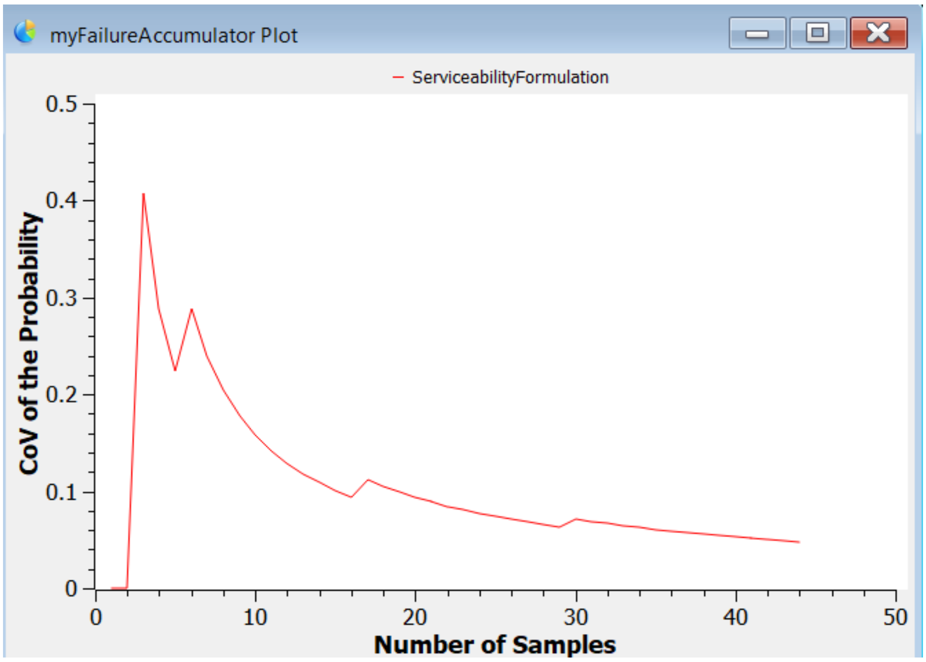


Fig. 5.27 Failure Accumulator Plot for Serviceability Formulation

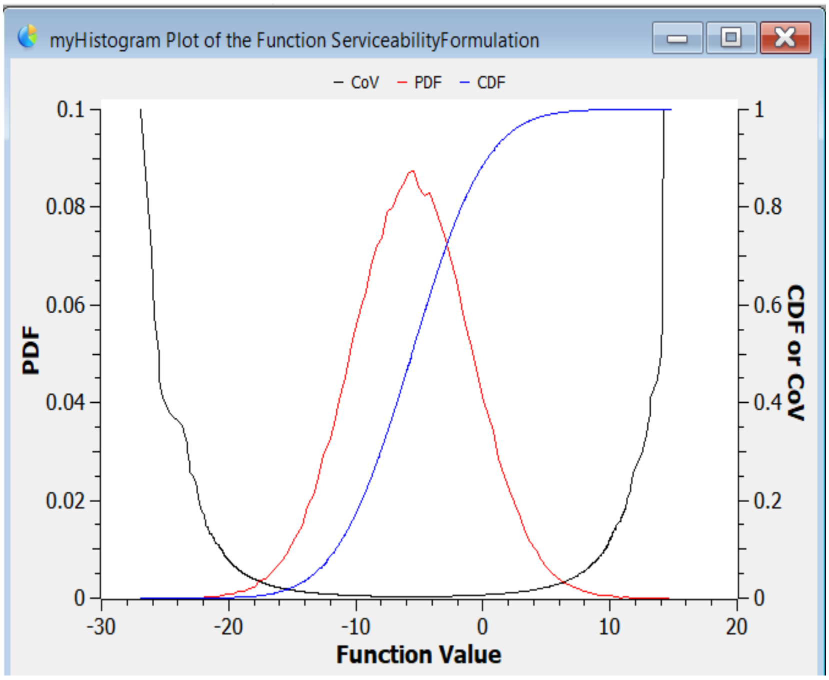


Fig. 5.28 Histogram Failure Plot for Serviceability Formulation

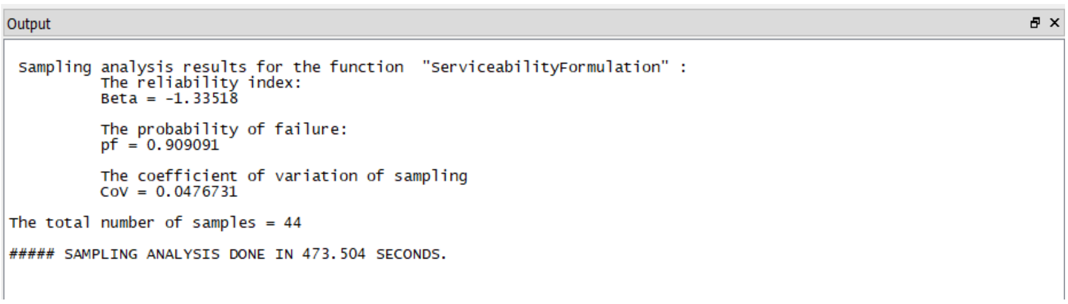


Fig.5.29 Output Results for Serviceability Formulation

CHAPTER -6

RELIABILITY ANALYSIS CONSIDERING WIND LOAD

6.1 WIND ANALYSIS

The Bureau of Indian Standards recommends using the IS code 875 (Part 3) 2015 for designing wind resistance structures. This code outlines the criteria for considering wind loads when designing various types of structures and their components. The wind load criteria depend on several factors, including wind pressure, terrain effects, local topography, and the size of the structures.

Structures are categorized into two types: tall buildings and low-rise buildings. Tall buildings are defined as structures with a height equal to or greater than 50 meters or a height-to-smaller dimension ratio exceeding 6. On the other hand, low-rise buildings are those with a structure height less than 20 meters.

To ensure the design of wind-resistant structures, the recommended code provides comprehensive guidelines that account for the specific wind pressures and environmental conditions applicable to the given project. These considerations are vital to create safe and structurally sound buildings capable of withstanding wind forces.

6.1.1 DESIGN WIND SPEED

Basic wind speed (V_b)for a site is obtained from IS 875-2015(PART-3) and is used to obtain the design wind speed (V_z) at any height.

$$V_z = k_1\, k_2\, k_3\, k_4\, V_b \tag{6.1}$$

Where,

V_z = Design wind speed at any height z (m/s)

V_b = Basic Wind Speed (m/s)

k_1 = probability factor (risk coefficient)

k_2 = terrain-roughness and-height factor

k_3 = topography-factor

k_4 = Importance of the-cyclone region

The basic wind map of India is shown in Fig.6.1

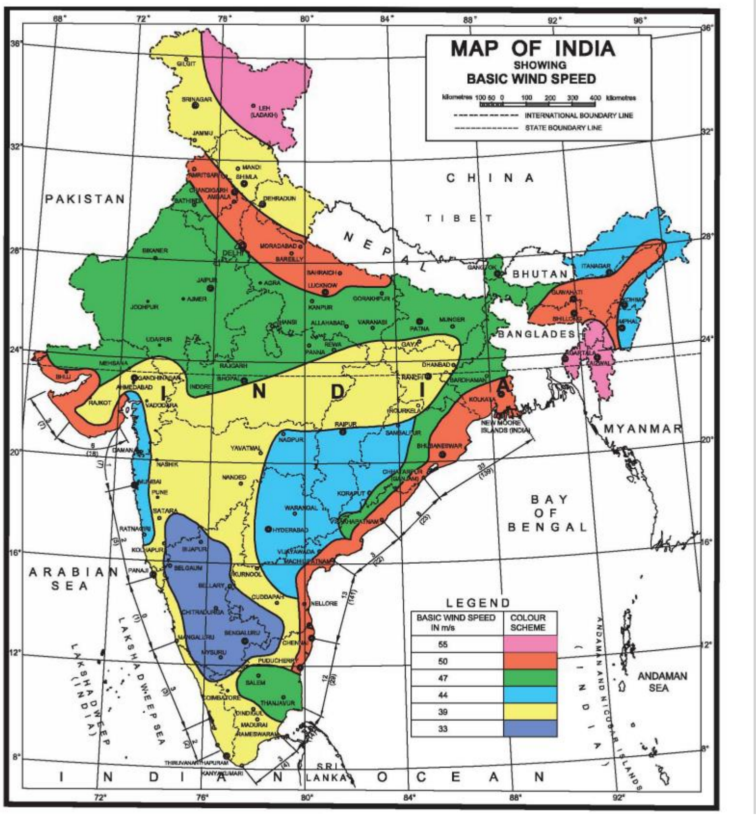


Fig.6.1 Basic Wind Speed based on 50-year Return Period [19]

6.1.2 Risk Factor (k_1)

The suggested life span to be assumed in design and the corresponding k_1 factors for different class of structures for the purpose of design are given in Table 6.1

Table 6.1 Risk coefficients for different classes of structures in different wind speed zones

Class of Structure	Mean Probable design life of structure in years	k_1 factor for Basic Wind Speed (m/s) of					
		33	39	44	47	50	55
All general buildings and structures	50	1.0	1.0	1.0	1.0	1.0	1.0
Temporary sheds, structures such as those used during construction operations (for example, formwork and false work), structures during construction stages, and boundary walls	5	0.82	0.76	0.73	0.71	0.70	0.67
Buildings and structures presenting a low degree of hazard to life and property in the event of failure, such as isolated towers in wooded areas, farm buildings other than residential buildings, etc.	25	0.94	0.92	0.91	0.90	0.90	0.89
Important buildings and structures such as hospitals, communication buildings, towers and power plant structures	100	1.05	1.06	1.07	1.07	1.08	1.08

6.1.3 Terrain and Height Factor

The selection of terrain categories should consider the impact of obstructions that contribute to the roughness of the ground surface. The choice of terrain category for designing a structure may vary depending on the wind direction being considered. If there is adequate meteorological data available regarding the wind direction, it is advisable to plan the orientation of buildings or structures accordingly. This ensures that the design factors in the specific wind conditions and optimizes the structural response to mitigate potential wind loads.

Table 6.2 k_2 factors to obtain design wind speed variation with height in different terrains.

Height (*z*) (*m*)	Terrain and height multiplier (k_2)			
	Terrain Category 1	Terrain Category 2	Terrain Category 3	Terrain Category 4
10	1.05	1.00	0.91	0.80
15	1.09	1.05	0.97	0.80
20	1.12	1.07	1.01	0.80
30	1.15	1.12	1.06	0.97
50	1.20	1.17	1.12	1.10
100	1.26	1.24	1.20	1.20
150	1.30	1.28	1.24	1.24
200	1.32	1.30	1.27	1.27
250	1.34	1.32	1.29	1.28
300	1.35	1.34	1.31	1.30
350	1.37	1.36	1.32	1.31
400	1.38	1.37	1.34	1.32
450	1.39	1.38	1.35	1.33
500	1.40	1.39	1.36	1.34
NOTE: For intermediate values of height z and terrain category, use linear interpolation.				

6.1.4 Topography Factor (k_3)

The topography factor is a crucial factor to consider when designing structures for wind resistance. It considers the influence of the local terrain on the wind loads experienced by a building or structure. Topography encompasses natural and man-made features of the land surface, such as hills, valleys, slopes, and nearby structures. Determining the topography factor involves analyzing the wind flow patterns and turbulence resulting from the interaction with the terrain. Factors like the shape and height of neighboring hills or structures, the distance between the structure and the topographic feature, and the wind direction are considered.

6.2 BUILDING MODEL

A G+10 Steel Framed Building is modelled in ETABS using appropriate Wind Data. The bending moments for column members are determined and the Limit state function for most critical column has been formulated using IS800: 2007.

The column is subjected to combined Axial forces and bending Moments. IS 800: 2007 Section 9 provides the details under clause 9.3.1.

The details of the building model, wind loading conditions are given in Tables below.

Building Data:

Storeys: G+10

Plan dimension : 16m × 16m

No. of bays in x-direction:4

No. of bays in y-direction:4

Length of each bay: 4m

Material Properties:

Steel Section : Fe345

Concrete (for slab section): M25

Deck Slab Thickness: 0.10m

Section Properties: STEEL I SECTION

Beam : ISLB200

Columns : ISMB450

Secondary beams: ISLB175

Fig.6.1 shows the plan of the building. The building model ,material properties, section properties are defined and the load cases are selected and shown in Fig.6.3 to Fig.6.6.

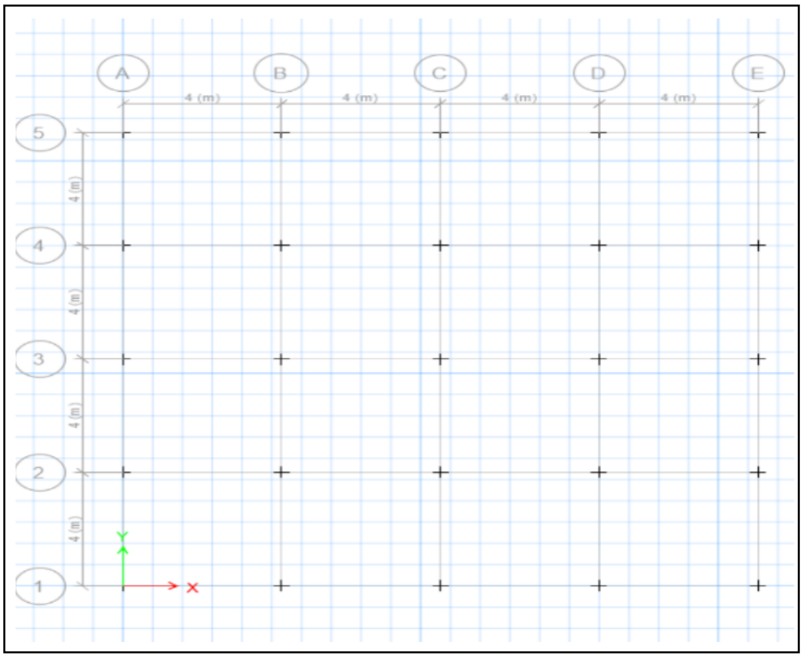


Fig.6.2 Plan of Building

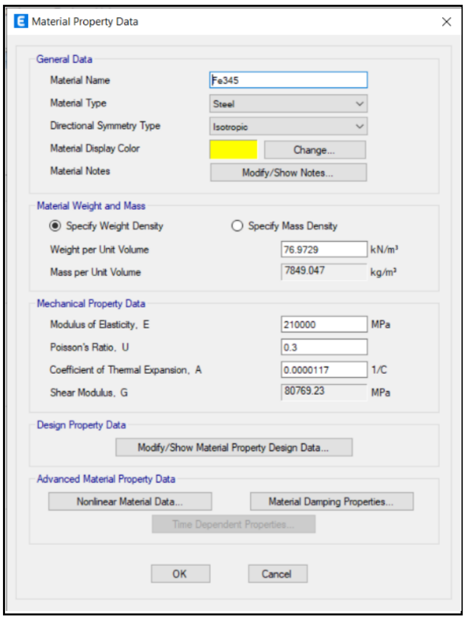


Fig.6.3 Material Property Data

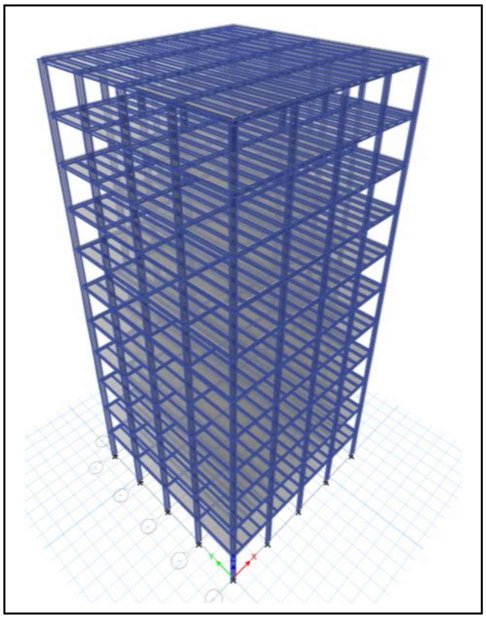


Fig.6.4 Rendered Building Model

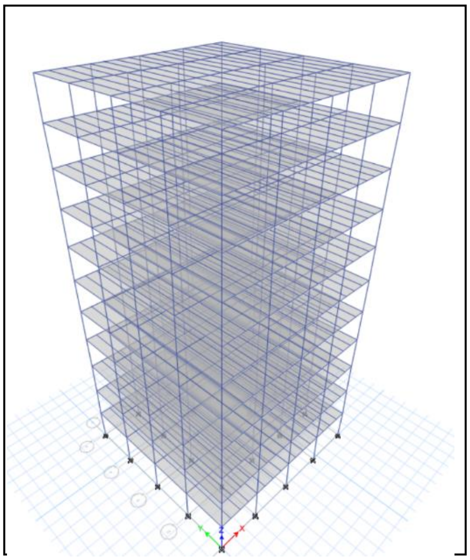


Fig.6.5 Beam, Column and Slab Properties Assigned

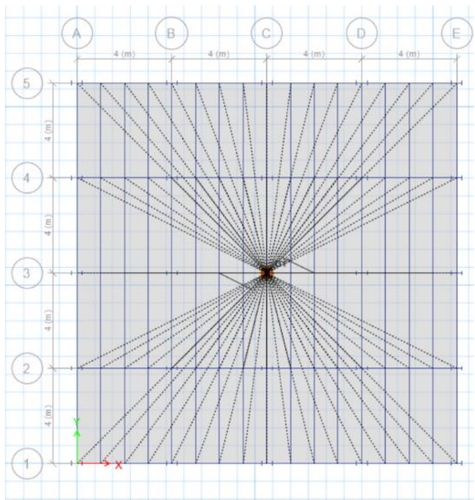


Fig.6.6 Building model completed with connected diaphragm.

6.2.1 Load Cases

Different load case combinations of Dead, Live, Wind Load have been applied to the building model as shown in Fig 6.7

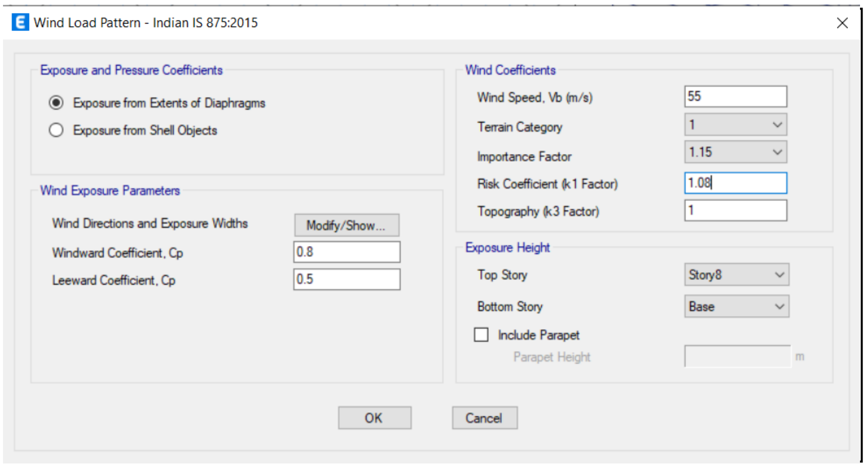


Fig.6.7 Wind Load Specification

Table.6.3 Wind Load Data: IS 875:2015

Wind Coefficients	**Values**
Wind Speed V_b (m/s)	55
Terrain Category	1
Importance Factor	1.15
Risk Coefficient(k1)	1.08
Topography(k3)	1

Table.6.4 Dead Load & Imposed Loading Data

Load Data	Values
Dead Load (Flooring Condition)(KN/m^2)	1.5
Live load on Slab(KN/m^2)	3
Frame Load Intensity (beam sections) (KN/m)	6

6.3 LIMIT STATE FUNCTION FOR CRITICAL COLUMN SUBJECTED TO COMBINED FORCES

As per IS800:2007 clause 9.3.1.1, Under combined axial force and bending moment, section strength as governed by material failure and member strength as governed by buckling failure shall be checked in accordance with

$$\left[\frac{My}{Mndy}\right]^{\propto_1} + \left[\frac{Mz}{Mndz}\right]^{\propto_2} \leq 1 \qquad (6.2)$$

where

M_y, M_z = Factored applied moments about the minor and major axis of the cross-section, respectively

M_{ndy} ,M_{ndz} =Design reduced flexural strength under combined axial force and the respective uniaxial moment acting alone

N =Factored applied axial force (Tension, T or Compression, P)

N_d = Design strength in tension, T_d or in Compression given by : $N_d = \frac{A_g.fy}{\gamma_{m0}}$

For standard I and H sections:

For $n \leq 0.2$, $M_{ndy} = M_{dy}$

For $n > 0.2$ $M_{ndy} = 1.56M_{dy}(1-n)(n+0.6)$

$M_{ndz} = 1.11M_{dz}(1-n)$

The values of $\propto_1$ and $\propto_2$ can be computed from Table 17. The values for Mdy and Mdz for ISMB450 are suitably calculated from IS800: 2007 (8.2)

The column section considered is ISMB450. The Limit state function for critical column member is formulated using IS 800: 2007 Section 9. The value for mean and standard deviation of Axial Force, and Biaxial moments is calculated using MS Excel.

The limit State Function formulated is given by equation (6.3)

$$1 - \left[\frac{M_y}{\left(86.19N - \left[\frac{N^2}{fy}\right] 0.0256 + 1084505.76fy\right)}\right]^{\left(0.000596\frac{N}{fy}\right)} - \left[\frac{M_z}{(206000fy - 24.7816N)}\right]^2 \quad (6.3)$$

The given function is used to calculate the reliability index and probability of failure.

6.3.1 Results In COMREL

```
*********************************************
--------- Comrel-TI (Version 2023) -----------
---- (c) Copyright: RCP GmbH (1989-2023) -----
*********************************************

-----------------------------------------------------------------------------
 Job name ........... :                                                 DEMO
 Failure criterion no. :       1
 Comment : No comment
 Transformation type    : Rosenblatt
 Optimization algorithm: RFLS
-----------------------------------------------------------------------------

 FORM-beta=   2.640; SORM-beta=   2.614; beta(Sampling)=   --     (IER=   0)
 FORM-Pf=  4.15E-03; SORM-Pf=  4.48E-03; Pf(Sampling)=    --

            --------- Statistics after COMREL-TI ---------
             State Function calls              =       82
             State Funct. gradient evaluations =    12
             Total computation time (CPU-secs.)=     0.03
             The error indicator (IER) was =    0
            *********************************************

 FLIM(1)    = -7.03512e-09

 N          = 1.45561e+06      Mean = 1.26202e+06     +15.3%
 My         = 179717           Mean = 207513          -13.4%
 Mz         = 3.94747e+07      Mean = 1.14965e+07     +243.4%
 fy         = 366.733          Mean = 375             -2.2%

Reliability analysis is finished
```

Numerical Results

```
DEMO.mti

 -----------------------------------------------------------------------------
   Job name ............ : DEMO
   Failure criterion no. :       1
   Comment : No comment
   Transformation type    : Rosenblatt
   Optimization algorithm: RFLS
   Date(dd.mm.yyyy) .... : 12.05.2023
   Time(hh:mm) ........  : 16:03
   Comrel-TI, (Version 2023), Copyright: RCP GmbH (1989-2023)
 -----------------------------------------------------------------------------

  Block beginning with Keyword $CHARVAL not found in Input-file !
  Characteristic Values default to mean values.

  Create buffer for $LIMFUNC with      3173 Bytes (Ier from Fstat =   0)

    ----------------------------------------
                COMREL-TI
    Iteration monitoring of YBETAU algorithm
    ----------------------------------------
       General environment information
       Maximal number of iterations in RFLS1 =     50
       Maximal number of iterations in RFLS2 =     50
       Type of numerical derivatives         =      0
       Precision for convergence criteria    =   1.0000E-03
```

```
Line search precision  =   1.0000E-01

Initial U-space solution
      0.0000      0.0000      0.0000      0.0000

Algorithm 1 : Iteration history
------------------------------------------------------------------------------
Iteration No.  1; CPU-seconds(cumulative):     0.012
 Scaled St.F(U) =  0.9305    ; BETA =      0.0000; BETA/||U||=      0.0000
------------------------------------------------------------------------------
Iteration No.  2; CPU-seconds(cumulative):     0.012
 Scaled St.F(U) =  0.8829    ; BETA =      0.7693; BETA/||U||=      0.7249
------------------------------------------------------------------------------
Iteration No.  3; CPU-seconds(cumulative):     0.016
 Scaled St.F(U) =  0.8402    ; BETA =      1.0612; BETA/||U||=      0.8435
------------------------------------------------------------------------------
Iteration No.  4; CPU-seconds(cumulative):     0.020
 Scaled St.F(U) =  0.8008    ; BETA =      1.2580; BETA/||U||=      0.8942
------------------------------------------------------------------------------
Iteration No.  5; CPU-seconds(cumulative):     0.023
 Scaled St.F(U) =  0.7639    ; BETA =      1.4067; BETA/||U||=      0.9219
------------------------------------------------------------------------------
Iteration No.  6; CPU-seconds(cumulative):     0.023
 Scaled St.F(U) =  0.6792    ; BETA =      1.5258; BETA/||U||=      0.8724
------------------------------------------------------------------------------
Iteration No.  7; CPU-seconds(cumulative):     0.023
 Scaled St.F(U) =  -1.299    ; BETA =      1.7489; BETA/||U||=      0.5262
------------------------------------------------------------------------------
Iteration No.  8; CPU-seconds(cumulative):     0.027
 Scaled St.F(U) = -0.3015    ; BETA =      3.3219; BETA/||U||=      1.1642
------------------------------------------------------------------------------
Iteration No.  9; CPU-seconds(cumulative):     0.027
 Scaled St.F(U) = -0.3153E-01; BETA =      2.8535; BETA/||U||=      1.0711
------------------------------------------------------------------------------
Iteration No. 10; CPU-seconds(cumulative):     0.031
 Scaled St.F(U) = -0.4707E-03; BETA =      2.6640; BETA/||U||=      1.0094
------------------------------------------------------------------------------
Iteration No. 11; CPU-seconds(cumulative):     0.031
 Scaled St.F(U) = -0.4582E-06; BETA =      2.6392; BETA/||U||=      1.0001
------------------------------------------------------------------------------
Iteration No. 12; CPU-seconds(cumulative):     0.031
 Scaled St.F(U) = -0.7744E-08; BETA =      2.6388; BETA/||U||=      1.0000

Statistics after RFLS-algorithm #1 (YRFLS1)
Cumulative seconds used        :       0.0312
Number of iterations           :     12

Statistics after RFLS-algorithm #1 (YRFLS1)
Cumulative seconds used         :       0.0312
Number of iterations            :     12
Cumulative gradient calls       :     12
Cumulative state function calls:      67
State function scaling          :   9.5411E-01

Statistics after beta-point search :
Cumulative seconds used         :       0.0312
Number of iterations(RFLS-1+-2):      12
Cumulative gradient calls       :     12
Cumulative state function calls:      67

Transfer to GUI: NBV=    4;   NPVEC=    0

-----Vector U-mem plus FU at solution                 -----
  0.7387          0.4221E-07       2.494          -0.4450          -0.7744E-08

-----Vector X at solution transfered to GUI           -----
  0.1456E+07      0.1797E+06      0.3943E+08       366.5

-----Vector of constant Parameters transfered to GUI   -----


beta-value to GUI:        2.6388;   Pf-value to GUI:   4.1595E-03
```

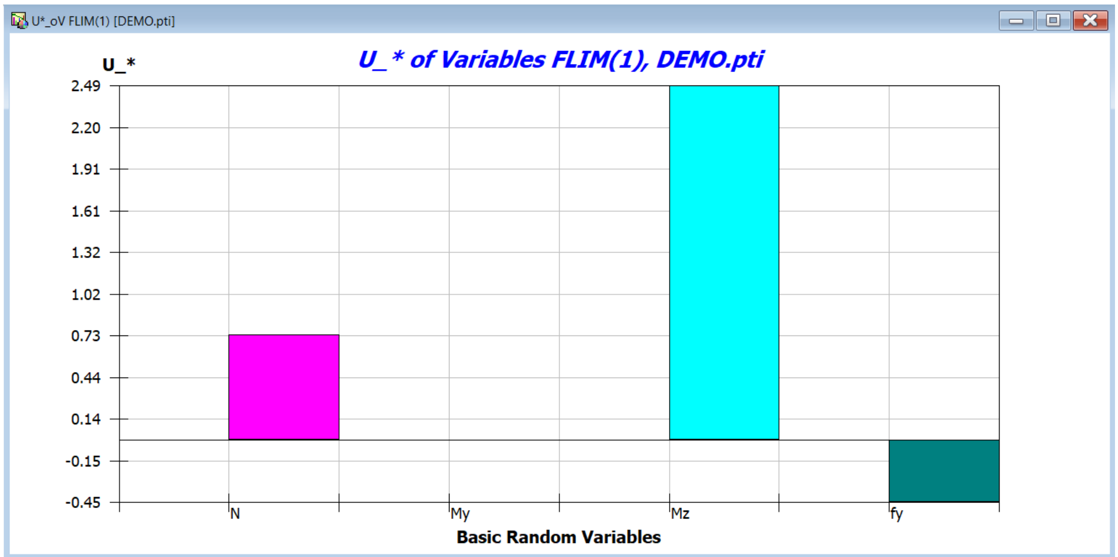


Fig.6.8 The co-ordinates of design points in standard normal space for each of the random variables.

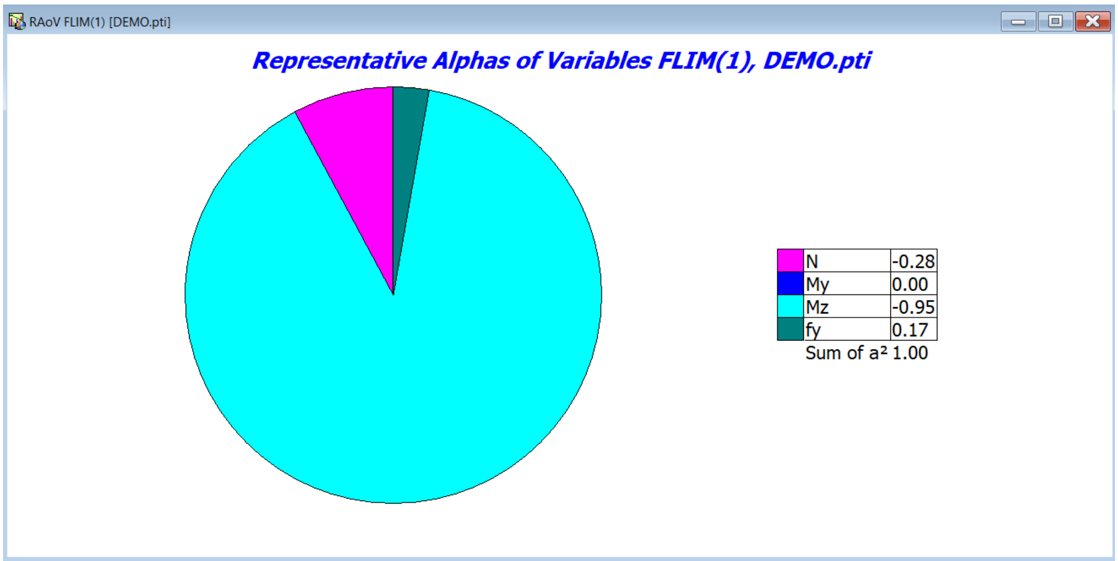


Fig.6.9 Influence Coefficients for defined Variables

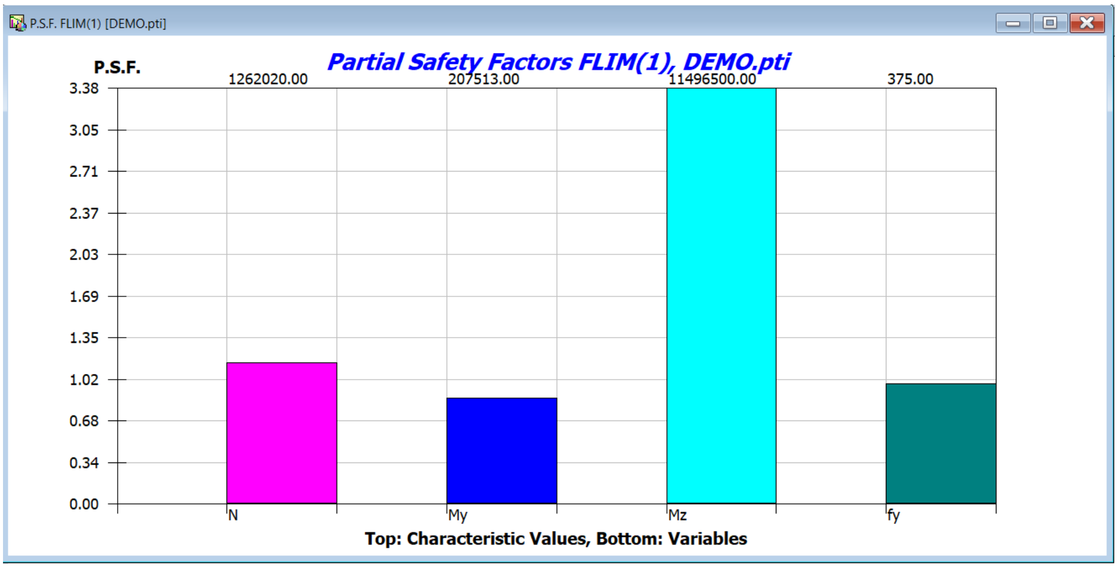


Fig. 6.10 Partial Safety Factors for Defined Variables

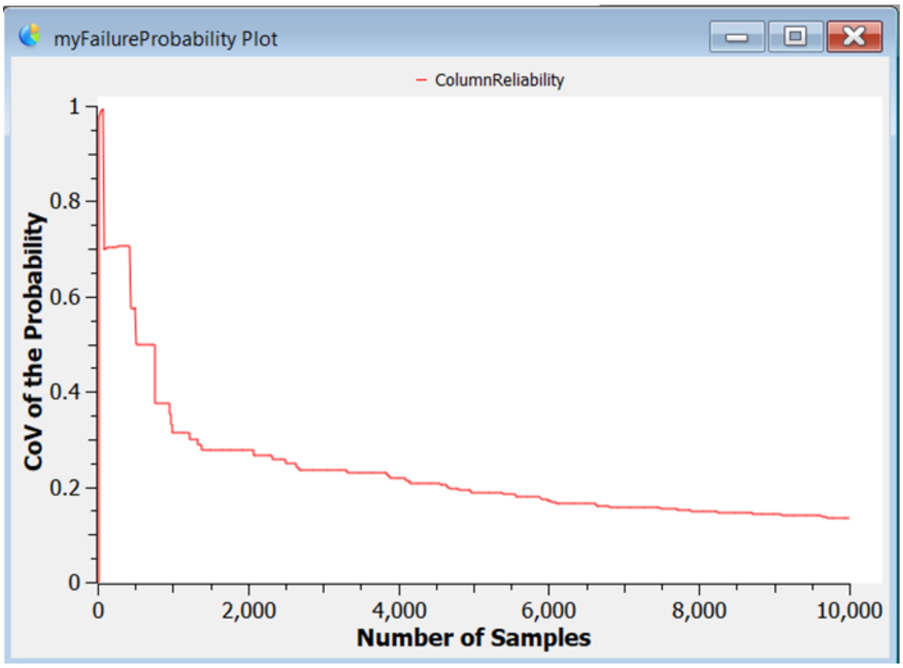


Fig. 6.11 Monte-Carlo Sampling Failure Plot for defined Function

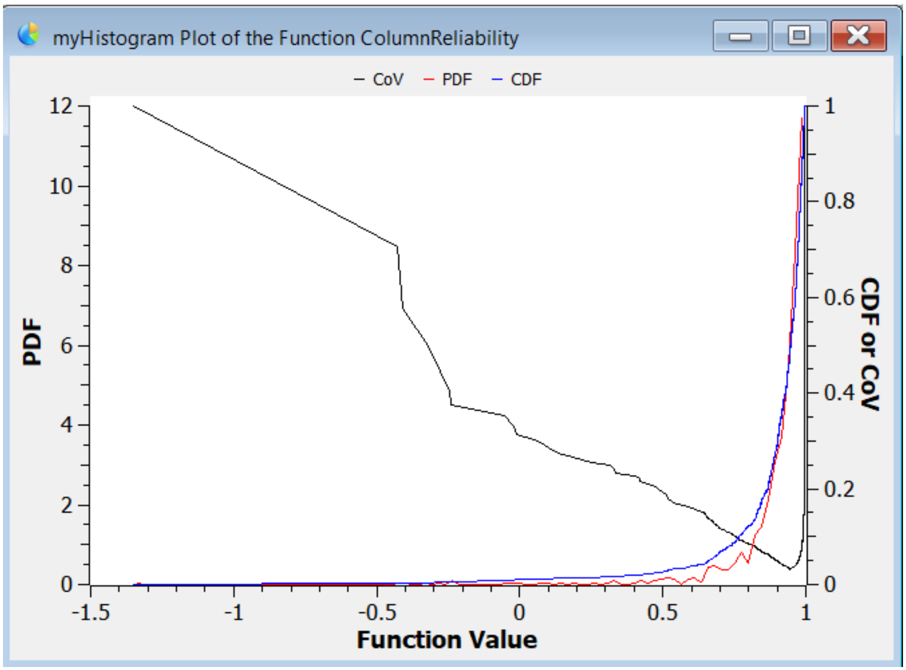
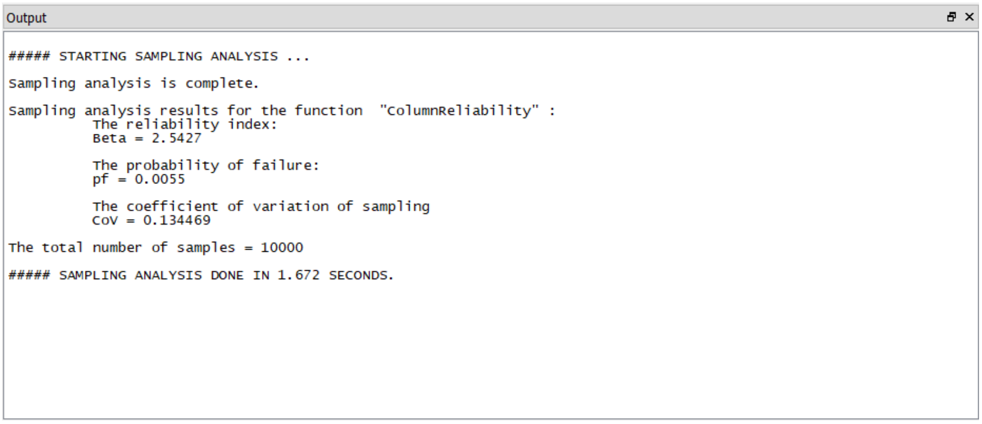


Fig.6.12 Histogram Failure Plot for defined Function



```
Output

##### STARTING SAMPLING ANALYSIS ...

Sampling analysis is complete.

Sampling analysis results for the function  "ColumnReliability" :
          The reliability index:
          Beta = 2.5427

          The probability of failure:
          pf = 0.0055

          The coefficient of variation of sampling
          CoV = 0.134469

The total number of samples = 10000

##### SAMPLING ANALYSIS DONE IN 1.672 SECONDS.
```

Fig.6.13 Output Results of Monte-Carlo Sampling for defined function

CHAPTER-7

SUMMARY AND CONCLUSIONS

The concept of Reliability Theory was studied and used to calculate the reliability of structural members under different cases. The limit state functions for a beam member under different conditions were formulated and the results were computed using different reliability methods such as FORM, SORM, MVFOSM and Monte-Carlo Sampling. The results were further calculated by using the COMREL programming and 'Rt' Reliability Program. The main conclusions drawn are:

- For the beam sections, manually determined reliability indices for various limit state formulations, such as strength, stress, serviceability, and shear, display a range of results. Therefore, it demonstrates that the first order second moment technique lacks invariance. The sensitivity of the issue to each of the random variables is expressed by the influence coefficients' absolute values. The sum of squares of influence coefficients is 1.

- Further, the analysis of a multi-storied steel framed building subjected to a specific wind load condition was done and the limit state function for the critical column member was formulated using IS 800-2007. The reliability index was calculated, and results were validated by COMREL programming and 'Rt' Reliability Program.

- In the calculated values of the Reliability index, the mere difference in these estimates shows that the limit-state surface is virtually flat around the design point in the space of the standard normal variables. Both FORM and SORM produce reliability index values that are close, with SORM's outcome being slightly more cautious or on the safe side.

- Determination of β value is an advanced process of estimation of failure of structural components. Value of β for column comes out to be 2.6388 which indicates a moderate Reliability level as inferred from different literatures and is little lesser than the target limit 3 specified in ANSI for dead and live load combination. This value comes in between ‘Some’ and ‘Moderate’ level of consequence of failure with P_f of the order 10^{-2} to 10^{-3}.

APPENDIX-1

Table A 1.1 Element Forces for Critical Column

ELEMENT FORCES FOR CRITICAL COLUMN					
Column	**Output Case**	**Type**	**P**	**M2**	**M3**
			kN	kN-m	kN-m
C2	UDStlS2	Combination	-1772.7956	-0.4577	29.2443
C2	UDStlS3	Combination	-1418.2365	-0.3661	23.3955
C2	UDStlS3	Combination	-1418.2365	-0.3661	23.3955
C2	UDStlS4	Combination	-1418.2365	-0.3661	23.3955
C2	UDStlS4	Combination	-1418.2365	-0.3661	23.3955
C2	UDStlS5	Combination	-1418.2365	-0.3661	23.3955
C2	UDStlS5	Combination	-1418.2365	-0.3661	23.3955
C2	UDStlS6	Combination	-1418.2365	-0.3661	23.3955
C2	UDStlS6	Combination	-1418.2365	-0.3661	23.3955
C2	UDStlS7	Combination	-1418.2365	-0.3661	23.3955
C2	UDStlS7	Combination	-1418.2365	-0.3661	23.3955
C2	UDStlS8	Combination	-1418.2365	-0.3661	23.3955
C2	UDStlS8	Combination	-1418.2365	-0.3661	23.3955
C2	UDStlS9	Combination	-1418.2365	-0.3661	23.3955
C2	UDStlS9	Combination	-1418.2365	-0.3661	23.3955
C2	UDStlS10	Combination	-1418.2365	-0.3661	23.3955
C2	UDStlS10	Combination	-1418.2365	-0.3661	23.3955
C2	UDStlS1	Combination	-1364.7406	-0.4145	20.3456
C2	UDStlS11	Combination	-1364.7406	-0.4145	20.3456
C2	UDStlS11	Combination	-1364.7406	-0.4145	20.3456
C2	UDStlS12	Combination	-1364.7406	-0.4145	20.3456
C2	UDStlS12	Combination	-1364.7406	-0.4145	20.3456
C2	UDStlS13	Combination	-1364.7406	-0.4145	20.3456
C2	UDStlS13	Combination	-1364.7406	-0.4145	20.3456
C2	UDStlS14	Combination	-1364.7406	-0.4145	20.3456
C2	UDStlS14	Combination	-1364.7406	-0.4145	20.3456
C2	UDStlD2	Combination	-1181.8637	-0.3051	19.4962
C2	UDStlD1	Combination	-909.827	-0.2763	13.5637
C2	UDStlS15	Combination	-818.8443	-0.2487	12.2073
C2	UDStlS15	Combination	-818.8443	-0.2487	12.2073

	UDStlS16	Combination	-818.8443	-0.2487	12.2073
C2	UDStlS16	Combination	-818.8443	-0.2487	12.2073
C2	UDStlS17	Combination	-818.8443	-0.2487	12.2073
C2	UDStlS17	Combination	-818.8443	-0.2487	12.2073
C2	UDStlS18	Combination	-818.8443	-0.2487	12.2073
C2	UDStlS18	Combination	-818.8443	-0.2487	12.2073

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